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EVALUATION OF MOBILE GASIFIERS

FOR THE

OTA OIL REPLACEMENT ANALYSIS PROJECT

November 1984

This is an OTA Working Paper that has been neither reviewed nor approved by the Technology Assessment Board.

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OTA WORKING PAPER

This report is an OTA Working Paper, which was used in the preparation of OTA's final assessment report. OTA makes these working papers available for the use of readers desiring a more detailed or technical discussion of an issues than can normally be accomodated in our final report. An an OTA working paper, this report has not been reviewed or approved by the Technology Assessment Board. The findings and conclusions expressed in the report are those of the authors and do not necessarily reflect the views of OTA, the advisory panel, or the Technology Assessment Board.

RASOR ASSOCIATES, INC.

EVALUATION OF MOBILE GASIFIERS FOR THE OTA OIL REPLACEMENT ANALYSIS PROJECT

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EXECUTIVE SUMMARY

- All major industrial nations, except the U.S., survived a massive petroleum shortfall during World War II in part by converting a million vehicles to run directly on coal, wood or charcoal using mobile gasifiers.

- These mobile gasifiers reached a high level of development by the end of the war, and could be used by the U.S. as a cost-effective alternative in an emergency petroleum shortfall.

- Based on the European experience, existing U.S. manufacturing capability, existing U.S. coal and wood supplies, and existing U.S. distribution systems could potentially replace 1.2 million barrels per day of oil equivalent (MMbdoe) within one year of an oil supply cutoff, 2.8 MMbdoe within two years, and 4.3 MMbdoe within three years, at 20% of manufacturers' capacity, if adequate plans and preparations are made before the emergency.

- There exists no significant production of mobile gasifiers in the U.S. at present, and the U.S. has no activity to evaluate this option or to prepare for its emergency implementation.

- Summary overview (in format of G&H Phase I Table IV-1):

Description	Commercialization Status	1900 Oil Replacement Potential, boe/d
Mobile gasifiers fueled with coal, wood or other local solid fuels.	No present production. Previous commercial technology can be rapidly activated if preparations are made.	4 MM within 5 years at 10% of manufacturers capacity, or within 3 years at 20%.

Order of Magnitude Costs		Major Noninstitutional Constraints	Major Institutional/ Regulatory/Constraints
Capital $/boe/d	Annual $/boe		
32,000*	31-68	• Coal and wood distribution. • Quality control of fuel. • Reduced vehicle performance.	• Conflicts with car warrantees. • Tunnel and bridge prohibitions. • Environmental regulations.

*Based on $1500 conversion cost and 2 gallon/day consumption (G&H estimate for private passenger cars). A not-uncommon 20 gallon/day for a commercial truck would give 3200 $/boe/d.

EVALUATION OF MOBILE GASIFIERS FOR THE OTA OIL REPLACEMENT ANALYSIS PROJECT

I. PREFACE

The Office of Technology Assessment (OTA) of the U.S. Congress is analyzing various options for minimizing the impact of a 3 to 4 million barrels per day (MMbbl/d) cutoff of U.S. oil imports. As part of this project, Rasor Associates, Inc., (RAI) is reviewing and evaluating mobile gasifiers as an oil replacement technology. OTA and another contractor, Gibbs & Hill, Inc., (G & H), are reviewing and evaluating all other potential oil replacement technologies for the project.

This evaluation of mobile gasifiers by RAI is based primarily on the survey, performed for the California Energy Commission by RAI[25], of previous world-wide experience with the mobile gasifier during World War II, and on recent in-house research performed on mobile gasifiers by RAI. Reference should be made to the primary sources of data for more detailed discussion of the subjects summarized here. An annotated Bibliography of the most useful publications is included as Appendix A. The format employed in the G & H study is adopted to facilitate comparison with the other oil replacement technologies evaluated.

Section II of this report reviews the aspects of mobile gasifier status and technology that are specifically required for the OTA analysis. Section III discusses scenarios for implementing the use of this technology for oil replacement in the 1985-1990 period.

II. BACKGROUND SURVEY

1.0 INTRODUCTION

As war approached in the mid-1930's, the governments of several industrial countries (notably England, France, Italy, Germany, Sweden and Japan), recognizing their heavy dependence on imported oil, instituted research programs on alternate internal combustion engine fuels. The surviving documents show that they rapidly concluded that small mobile gasifiers (also known as "gas producers"), using their abundant indigenous solid fuels, were the only viable and practical alternative. These governments then initiated or subsidized development of such gasifiers in preparation for their mass production and use when petroleum supplies were disrupted by World War II.

When the war broke out in 1939, only about 100 vehicles powered by mobile gasifiers existed in Sweden, 700 in England, 2000 in Italy and 10,000 in France. This early experience was extremely important, however, because it prepared the technology base for the astonishingly rapid increase in the use of these systems during the subsequent war years.

Comprehensive data on the world-wide use of mobile gasifiers are not available, but it is estimated that by 1943, a total of nearly one million vehicles were powered by such systems. An excellent record of the Swedish experience with mobile gasifiers is available as summarized in Fig. 1 [(1)]. This experience can be considered to be typical for present purposes because, as described below, the circumstances in Sweden during World War II were a microcosm of the situation which may confront the U.S. in the next decade.

The experience in most countries qualitatively followed Fig. 1 in that the most rapid growth occurred over a period of about a year after a sudden cut-off of the petroleum supply and/or an abrupt rise in the price of gasoline. In Sweden for example, the use of mobile gasifiers grew from a few per cent of all its vehicles in mid-1940, when its oil supply was first interrupted, to about 40% in mid-1941. Within that year, about 30% of its cars and about 50% of its trucks and buses converted to use of mobile

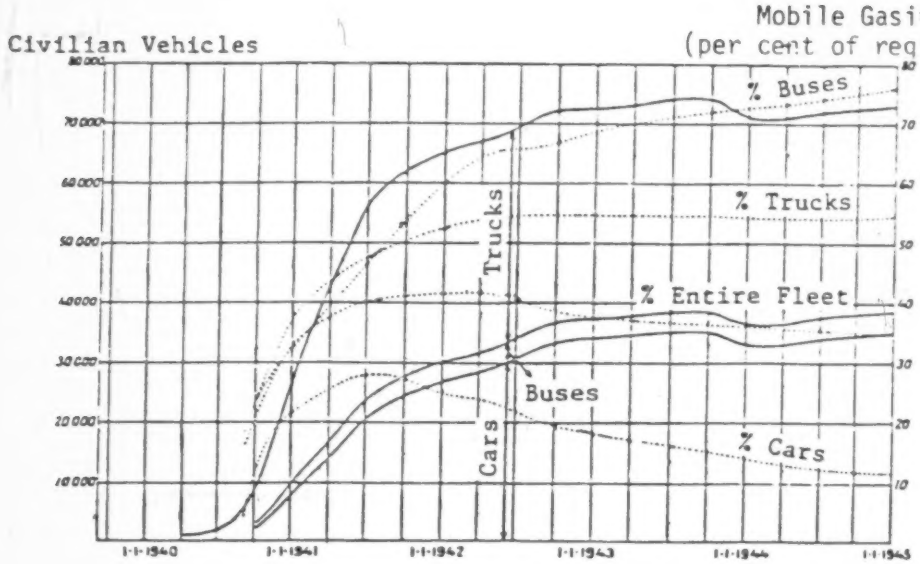

Fig. 1 Conversion of road vehicles to mobile gasifier operation in Sweden during World War II. Does not include 10,000 military vehicles, 15,000 tractors (out of 28,000), and 1000 motorcycles.

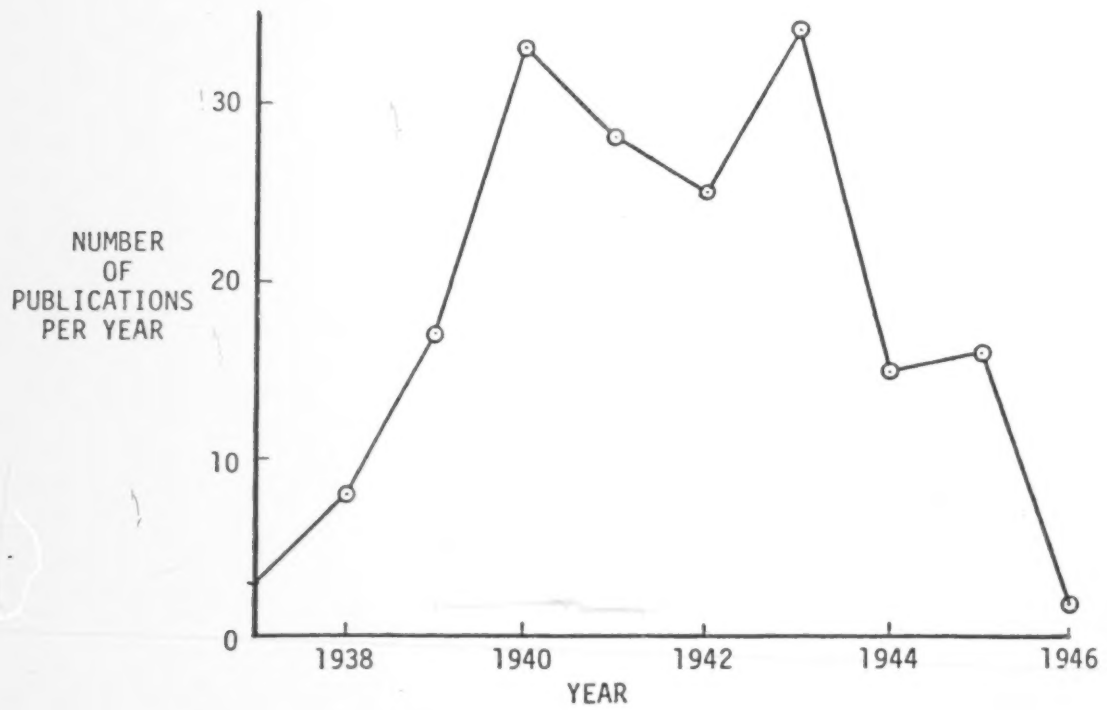

Fig. 2 Number of references cited in the Engineering Index each year under "Automotive fuels: producer gas" and "Gas producers: automotive". Total number of references during period shown was 168.

gasifiers.* In France this took place earlier (~1939), and in Germany, Japan and England later (~1943), when their petroleum supplies became effectively embargoed. As a result, many of the early systems used by other countries adopted or closely resembled the French designs, but superior designs subsequently evolved.

Almost all mobile gasifiers dissappeared completely within one year after the end of the war when abundant petroleum-based fuels, at a per-mile price lower than that of the mobile gasifier fuels, became universally available. As indicated by the rate of technical publications in Fig. 2, a large amount of research and development on mobile gasifiers occurred during the war. However, the few publications thereafter have been either reviews of the previous work or reports of isolated revivals of World War II models (primarily by hobbyists).

In addition to their use in road vehicles, mobile gasifiers were used in a wide variety of rail, marine, farm and other off-road vehicles during World War II. Similarly, a wide variety of internal combustion engine types were adapted to run on mobile gasifiers, and a wide variety of solid fuels were used. The type of fuel used was dependent on the most abundant indigenous solid fuel in a particular country: for example, Sweden had little coal but used wood fuels from its extensive forests; England had few forests, but used its abundant coal as mobile gasifier fuel; Germany had both fuels and used both in gasifiers. These applications, adaptations and fuels are listed in Fig. 3.

---

*Further utilization by passenger cars was inhibited after mid-1941 by restrictions on private use due to wartime shortages of tires and motor oil.

Fig. 3 SUMMARY LIST OF APPLICATIONS OF MOBILE GASIFIERS DURING WORLD WAR II.

1.0 Types of Engines Which Have Been Operated with Mobile-type Gasifiers

- 1.1 Unmodified and modified spark ignition carburetor-type engines.
  - 1.11 4-cycle
  - 1.12 2-cycle
- 1.2 Modified spark-ignition injection-type engines.
- 1.3 Modified Diesel engines.
  - 1.31 True 4-cycle Diesel
  - 1.32 Antechamber
  - 1.33 2-cycle (ignition bulb)

2.0 Applications in Which Mobile-type Gasifiers Have Been Used

- 2.1 Road Vehicles of All Sizes and Uses
  - 2.11 Automobiles
  - 2.12 Trucks and vans
  - 2.13 Buses
  - 2.14 Motorcycles
- 2.2 Off-Road Vehicles
  - 2.21 Farm tractors
  - 2.22 Road graders
  - 2.23 Rail switch engines
  - 2.24 Commuter trains
- 2.3 Marine Vessels
  - 2.31 Ships (fishing vessels, tugboats, other general utility vessels)
  - 2.32 River barges
  - 2.33 Recreational motorboats
- 2.4 Stationary Installations (wide variety of industrial and farm uses, ranging from small power saws to small electric power plants).

3.0 Fuels Which Have Been Used in Mobile Gasifier Systems

- 3.1 Coal-related (mineral) fuels
  - 3.11 Coal of all types (anthracite, bituminous, lignite)
  - 3.12 Coke (low and high temperature)
  - 3.13 Peat
- 3.2 Wood-related fuels
  - 3.21 Dried wood of all varieties
  - 3.22 Charcoal
  - 3.23 Waste products of saw and paper mills
- 3.3 Carbonaceous Wastes
  - 3.31 Petroleum coke
  - 3.32 Agricultural wastes

4.0 Countries Which Have Been Major Users of Mobile Gasifier Systems

England	Sweden
France	Denmark
Germany	Norway
Austria	Japan
Italy	Australia
USSR	Argentina
India	Switzerland

2.0 DESCRIPTION

2.1 Basic System

Fig. 4 schematically shows the major elements in a gasifier - internal combustion engine system that operates exclusively on solid fuel. Fig. 5 shows a similar bi-fuel system that also can operate on liquid fuel for starting and for intervals requiring high performance.

Since gas is drawn through the system by the engine intake, the entire gasifier system operates below atmospheric pressure. Primary air is drawn first into the gasifier where its oxygen reacts with coal at high temperatures to form a low-Btu fuel gas (110-160 Btu/scf) commonly known as "producer gas." The composition of high quality, dry producer gas is typically 20-30% CO, 10-20% H_2, 0.2% methane, 2-15% CO_2, and 45-60% N_2, depending on the type of gasifier and fuel. The fuel gas is passed through a cooler and filter, and is mixed in a gas carburetor with sufficient additional (secondary) air to obtain a stoichiometric mixture which is then throttled into the engine intake manifold.

After cooling, the fuel gas typically retains about 80% of the heat content of the coal. Spark ignition engines require no modification to operate on producer gas, although the power of such engines typically is reduced to 60-70% of their rated power on gasoline at the same RPM. Typical compression ignition (e.g., Diesel) engines require modification, but retain their full rated power when using producer gas.

Each of the components of the system now will be briefly discussed.

2.2 Gasifier

The conversion of solid fuels to producer gas dates back to the mid-19th century, and medium and large-scale gasifiers are still in use for stationary industrial and power plant installations.* The technology of small-scale

*See Appendix F and Appendix J-2 of the G & H Phase I report.

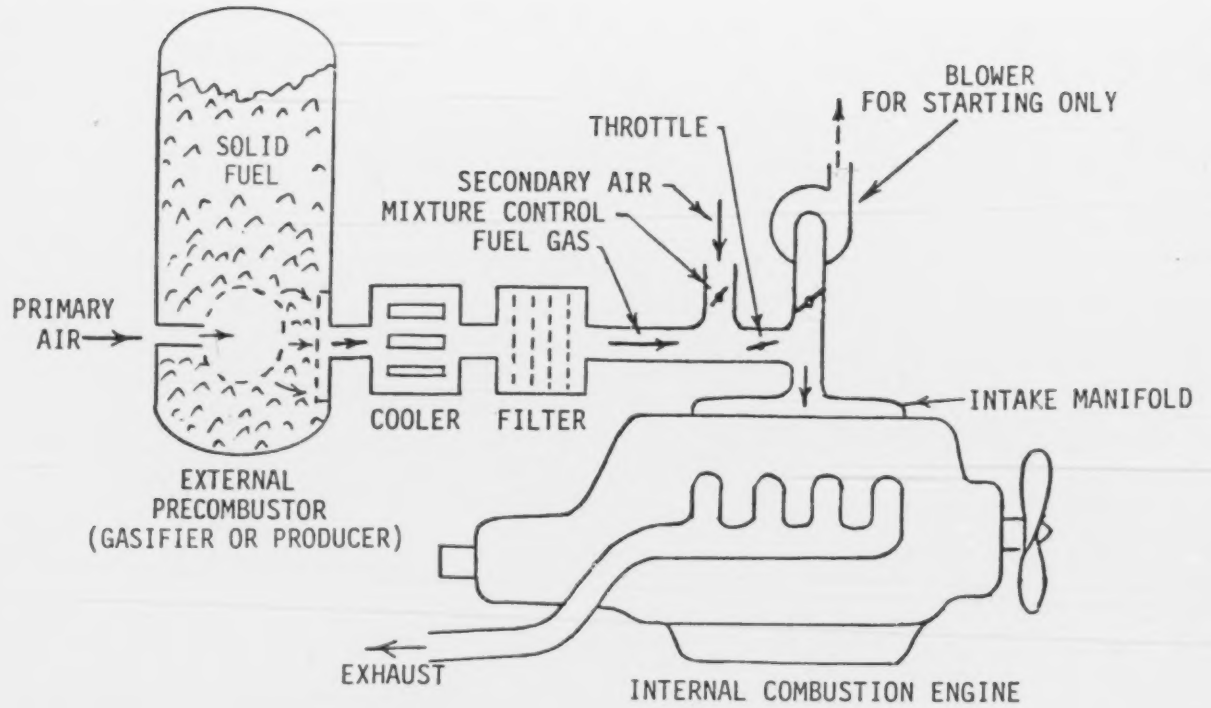

Fig. 4 Basic elements of the gasifier-engine system.

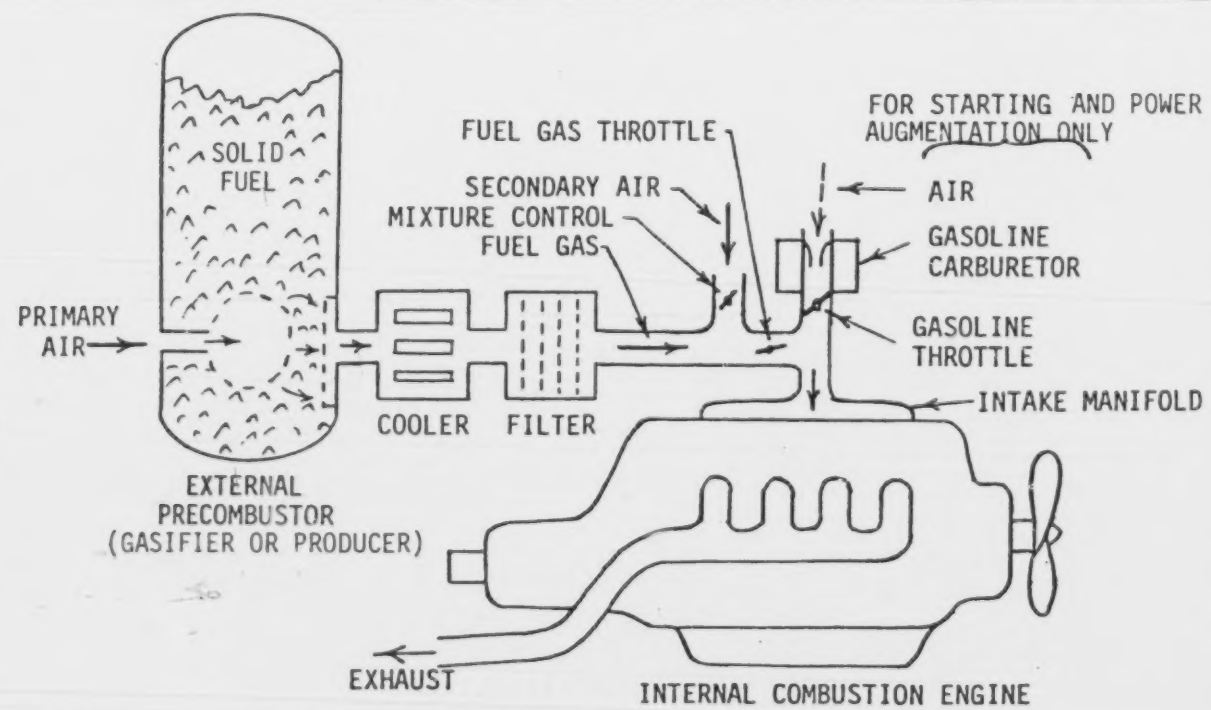

Fig. 5 Bi-fuel gasifier-engine system.

mobile gasifiers is significantly different from these larger stationary systems in several respects, however. These differences arise primarily because a much smaller combustion region is required in the mobile system in order to achieve a practical size for mounting on the vehicle, and to obtain a short response time over the wide range of throughput demands which characterize the operation of vehicle power plants. This combination of a small reaction volume and high throughput capability implies a very short time of contact between the air and the solid fuel. As shown in Fig. 7, this imposes a requirement for much higher operating temperatures in mobile gasifiers than in large stationary gasifiers in order to obtain the high quality fuel gas and high conversion efficiency that mobile systems require. Also, the mobile gasifier must not produce large quantities of engine-fouling materials such as tar and ash (smoke), since it is not practical to carry a large gas clean-up system on the vehicle.

Fig. 6 shows the basic gasifier configurations that characterize most of the mobile gasifiers used during World War II, and Fig. 8 shows typical specific examples that were mass-produced in different countries. The updraft type is essentially a scaled-down version of large stationary gasifiers[3]. Although employed initially by the British, this type was neither very successful nor widely used as a mobile gasifier because of its relatively large size and weight, poor response time and poor tolerance of tar-producing fuels. The downdraft[6] and crossdraft[4] types, that were developed specifically for mobile gasifier use, confine the combustion region to a smaller volume and reduce tar evolution by forcing volatiles to pass through the combustion region. Downdraft designs were used with a variety of fuels but were the most widely used type for wood and charcoal fuels. Crossdraft designs were the most widely used type for relatively low reactivity fuels such as coke and anthracite coal because single-tuyere air injection gives a very high temperature reaction region, and because the absence of convergent flow makes it relatively tolerant of fuel swelling and caking.

As experience was accumulated in actual use, "hybrid" designs were developed which combined the most attractive features of the downdraft and crossdraft types, as in the examples shown in Fig. 9. Although these

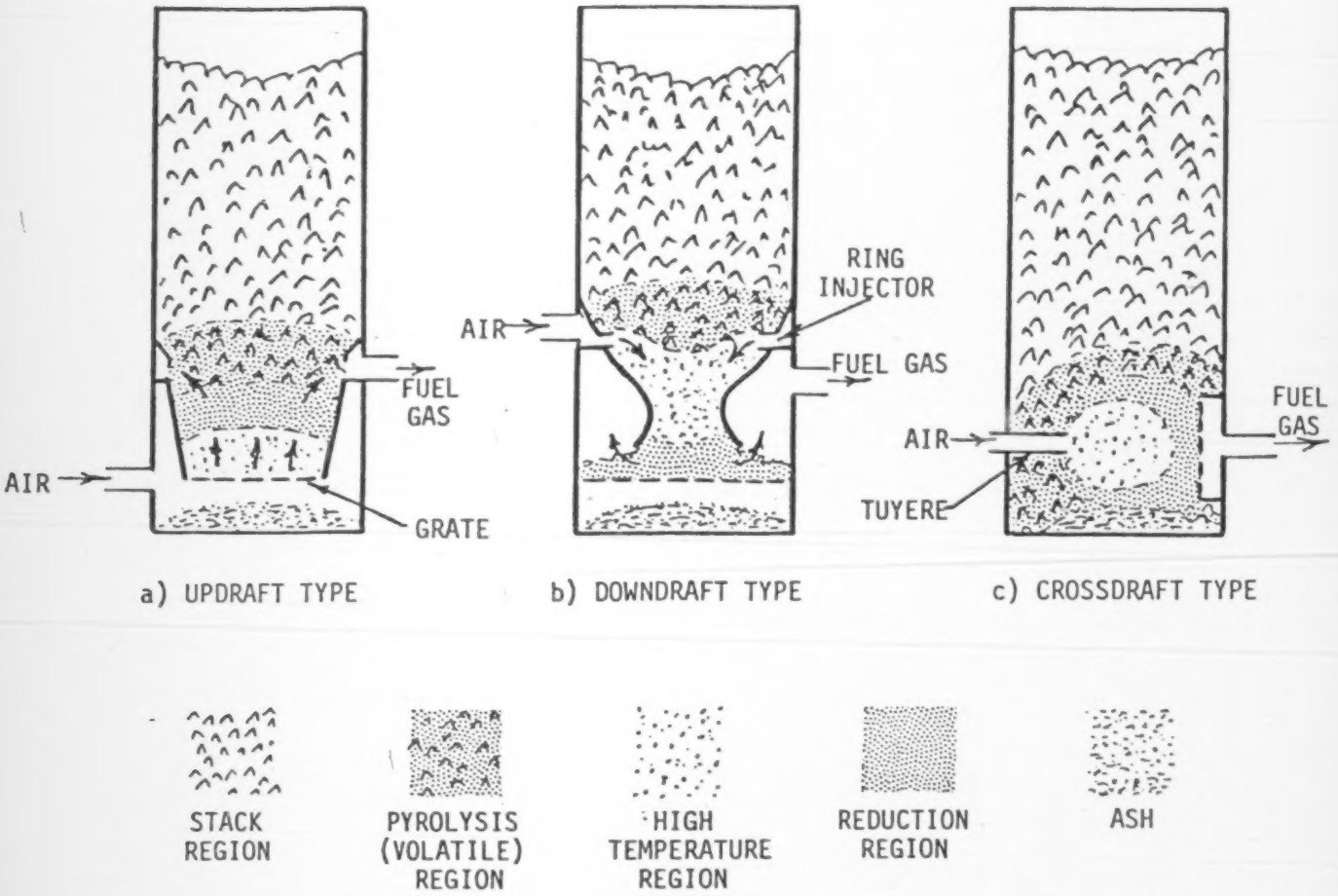

Fig. 6 Basic types and characteristic regions of mobile gasifiers.

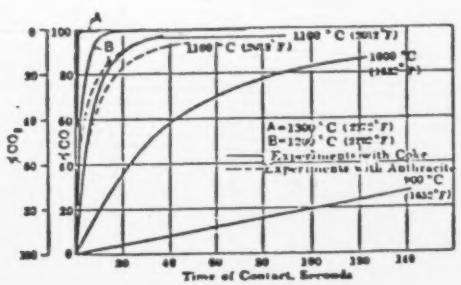

Fig. 7 Conditions affecting composition of producer gas.

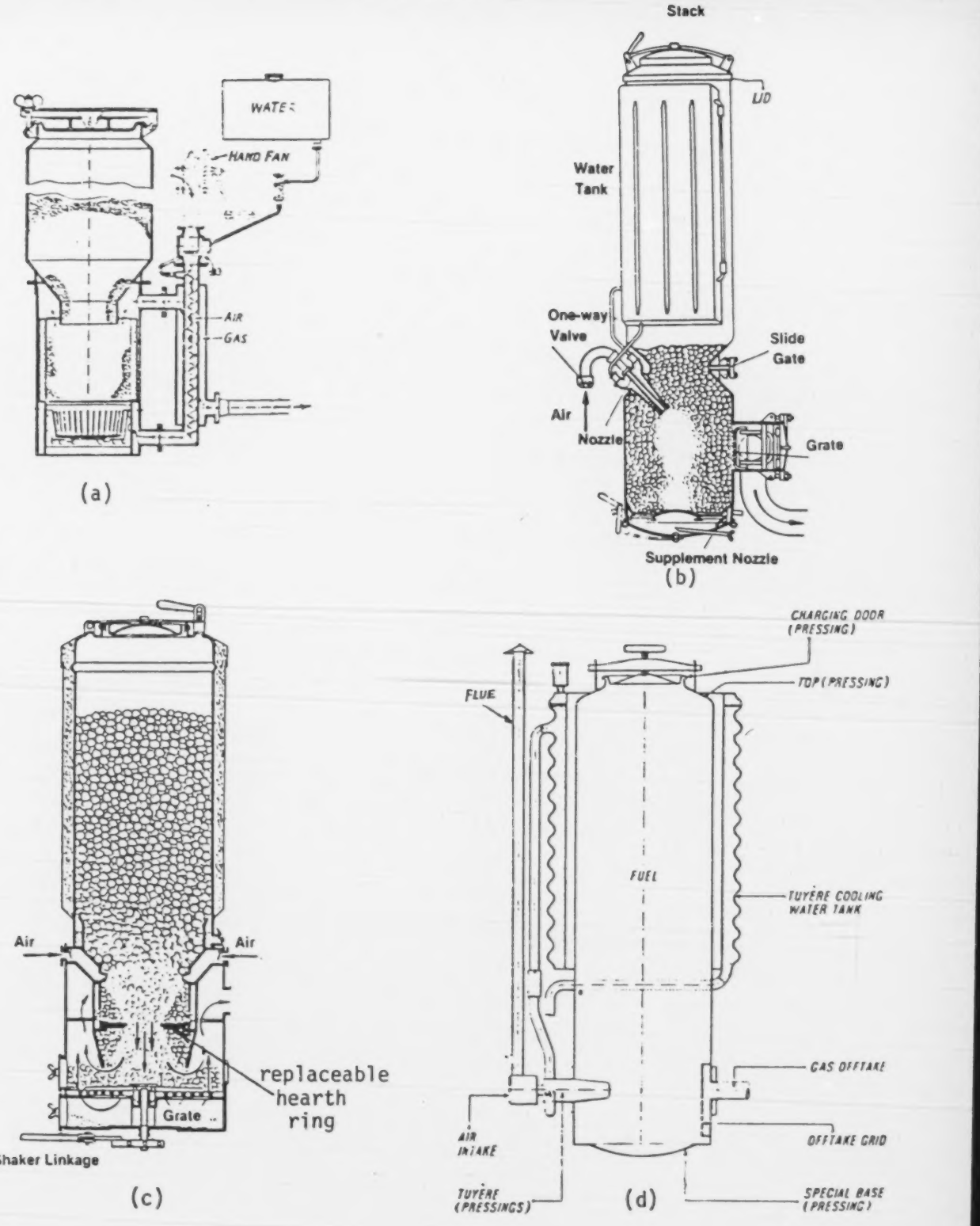

Fig. 8 Popular World War II mobile gasifier designs.

(a) Coal-fueled British Brush-Koela updraft gasifier.

(b) Coal and coke-fueled German Mercedes-Benz cross-draft gasifier.

(c) Wood-fueled German Zeuch downdraft gasifier.

(d) Coal-fueled British government-designed cross-draft gasifier. ("pressing" = stamping).

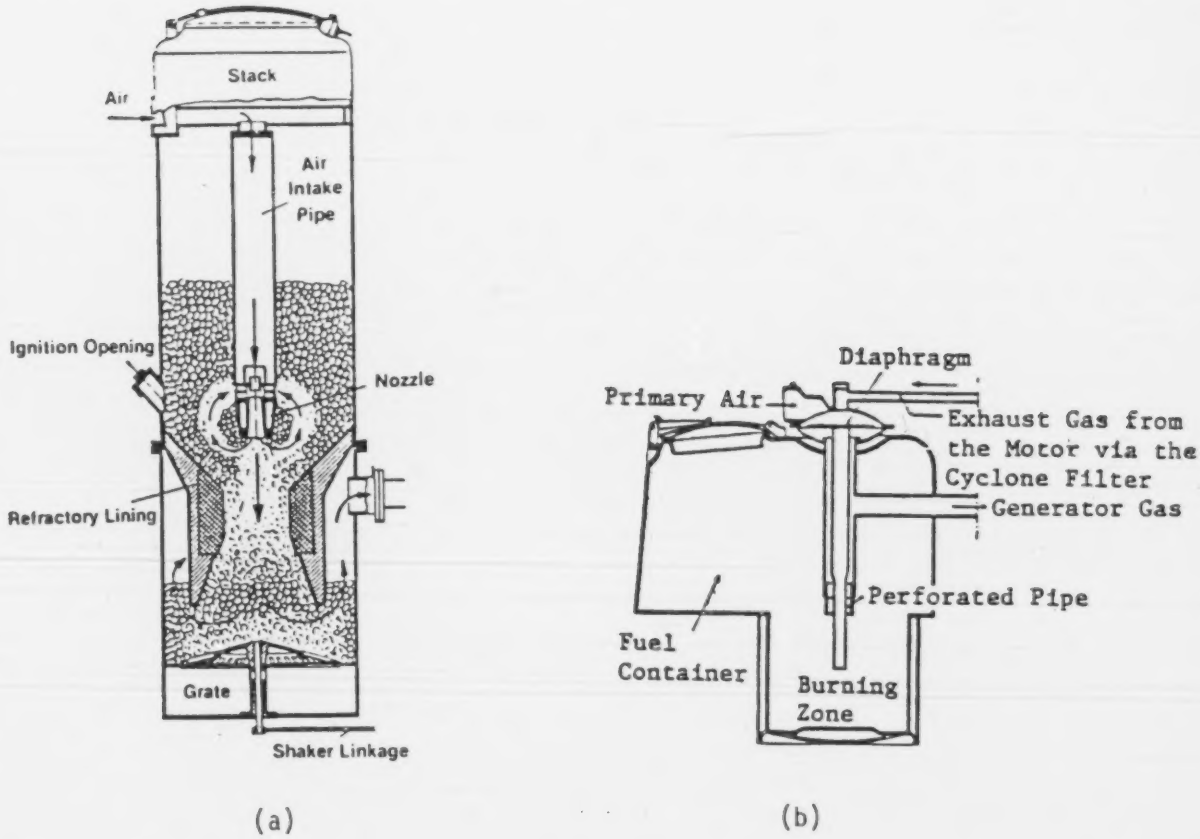

Fig. 9 Hybrid mobile gasifiers combining single axial tuyere with downdraft and updraft principles.

(a) German Zeissl design.

(b) Swedish Kalle design.

greatly-superior hybrid types began displacing the earlier types, the war ended before they could be as widely used. Accordingly, it is important to recognize that mobile gasifier technology advanced very rapidly during the 5-year war period, and that most of the extensive experience accumulated during that period was with the early primitive technology. Estimates which extrapolate that experience to the current situation therefore should include the effect of the more advanced technology on the utility of mobile gasifiers for present purposes.

The basic operation and features of the various mobile gasifier types are compared in more detail in References 1, 18 and 25, and are summarized in Fig. 10.

Although the reaction kinetics in mobile gasifiers are poorly understood because conditions are far from equilibrium, the basic gasification process is readily understood on the basis of the following (oversimplified) reactions and heat balance. An ideally efficient gasifier (negligible sensible heat losses) would decompose a medium-high-volatile coal (e.g. $CH_{.8}$ mole equivalent) and convert all of the carbon to CO via the approximate gasification reaction

$$\text{solid } CH_{.8} + (\text{air}) \xrightarrow{-2.4} C + .4H_2 + (\tfrac{1}{2}O_2 + 2N_2) \xrightarrow{28.3} CO + .4H_2 + 2N_2$$

where the heat release (+) is given in kilocalories per mole of coal. Complete combustion of this gas in the engine would give

$$CO + .4H_2 + 2N_2 + (.7O_2 + 2.8N_2) \xrightarrow{90.9} CO_2 + .4H_2O + 4.8N_2$$

Accordingly, 28.3-2.4 = 25.9 kilocalories of heat are wasted in the first reaction to gasify each mole of carbon into 3.4 moles of air. If 3.5 moles of air are added to this gas, 90.9 kilocalories of heat are released when the mixture is combusted in the engine to yield 6.2 moles of exhaust gas. Of the total of 117 kilocalories released, 90.9 (or 1.2 Mcal/Nm^3 = 135 Btu/scf) are available to the engine, so that the overall ideal thermal efficiency of the gasifier portion of the process is about 78%.

Fig. 10

SUMMARY COMPARISON OF GENERIC TYPES OF MOBILE GASIFIERS

CHARACTERISTICS	UPDRAFT	DOWNDRAFT	CROSSDRAFT
FUEL TOLERANCE			
Swelling and Caking	poor	poor-good	good
High Tar Content	poor	good	poor-good
Low Reactivity	poor	good	excellent
High Ash Content	excellent	good	good
STARTING	poor	good	excellent
RESPONSE TIME	poor	good	excellent
SIZE AND WEIGHT	poor	good	good
SIMPLICITY (cost)	poor	poor	excellent
SERVICING			
Short term	excellent	good	poor-good
Long term	good	good	excellent
GAS QUALITY (Composition) EFFICIENCY, SAFETY, LIFETIME	Properly designed and operated on fuels for which they are designed, the various generic types of gasifiers have essentially no significant differences in these characteristics.		
MEAN RELATIVE MERIT Poor=0 Good=1 Excellent=2	.5	.85	1.4

The equivalent description for ideal gasification of wood (mole equivalent $CH_{1.4}O_{.6}$) is

$$CH_{1.4}O_{.6} + (.2O_2 + .8N_2) \xrightarrow{11} CO + .7H_2 + .8N_2$$

and combustion in the engine gives

$$CO + .7H_2 + .8N_2 + (.85\ O_2 + 3.4\ N_2) \xrightarrow{108} CO_2 + .7H_2O + 4.2N_2$$

The ideal heat content of the fuel gas in this case therefore is about 210 Btu/scf, and the overall ideal efficiency (for negligible sensible heat loss) is about 90%.

Although perfectly dry wood therefore would be significantly superior to a medium-high-volatile coal, the relatively high moisture content of cost-effectively dried wood (10-25%) tends to degrade the gas heat content and efficiency of wood gasifiers to be comparable to that of coal gasifiers. Gas heat content in the 125-150 Btu/scf range and overall efficiencies of 70-80% characterize the operation of most types of mobile gasifiers with practically usable fuels. Table A illustrates the range of gas compositions and heat contents obtained with various types of fuels[8].

TABLE A

EXAMPLES OF GAS PRODUCED FROM VARIOUS FUELS

Fuel	Gasification Method	Percentage by Volume					Measured Heat Content	
		Combustible			Non-Combustible			
		CO	H_2	CH_3	CO_2	N_2	kcal/Nm³	Btu/scf
Wood (15% moisture)	Downdraft	22.2	17.5	0.8	12.2	47.3	1190	134
Wood (25% moisture)	Downdraft	23.0	14.1	0.9	16.0	45.9	1130	127
Charcoal	Updraft	30.4	19.7	—	3.6	46	1430	161
Peat	Downdraft	19.0	11.2	1.0	14.0	54.8	950	107
Lignite Briquettes	Downdraft	22.8	14.0	1.0	12.3	49.9	1140	128
Lignite Coke	Updraft	30.4	11.2	0.4	2.0	54.8	1280	144
Hard Coal Coke	Updraft	25.6	20.8	—	5.1	48	1350	152
Anthracite	Updraft	27.0	12.7	0.7	3.9	55.7	1200	135
	Crossdraft	24.4	8.9	0.6	2.8	61.9	1020	115

Considerable attention has been given in the literature to the use of air preheat, water injection and catalysts to improve the gas quality and efficiency of mobile gasifiers. The general conclusion which can be reached from the published work[4] is that these approaches can result in considerable improvement in the gas quality from inferior fuels and from gasifiers of inferior reaction design, i.e. those which do not achieve the temperatures and reaction times required for the above-cited reactions to approach completion. With good fuels used in properly-designed gasifiers that approach the above-cited gas quality and efficiency, the improvement obtained is so small as to be of sub-marginal value considering the additional cost and complexity. On the other hand, water injection with air

preheat can be useful if the hearth temperature must be limited below the value giving good CO production, e.g., to not fuse the ash or exceed a component temperature limit. The loss in CO heating value at the lower temperature will then be compensated by the increased heating value of the free hydrogen produced. Also, preheating moist fuel (e.g. green wood) with waste heat from the cooler to remove excess moisture before combustion can be important to efficiency if such fuels must be used.

The factors affecting gasifier design are well documented[1-6,18]. The summary report of the Swedish experience[1] and the recent review by Kaupp and Goss[18] are by far the most comprehensive, and include detailed scaling rules for selection of the gasifier diameter and the fuel area constriction ratio vs gasifier flow capacity for downdraft gasifiers.

2.3 Cooler

The fuel gas leaves the gasifier at a temperature of about 300-500°C (500°C at full throttle operation) and must be cooled to the lowest practical temperature (typically 40°C) before mixing with secondary air and introduction into the engine. Since about 20% of the heat content of the original fuel must be rejected (for an 80% efficient gasifier), and an internal combustion engine rejects about 35-50% of its input fuel energy to its radiator, the size of the gas cooler is comparable to the size of the usual vehicle radiator. Provision must be made for collecting and draining of water and other vapors that condense in the cooler.

2.4 Filter

After leaving the cooler, any entrained particles (tars, ash and char) must be removed by a filter before the gas is introduced into the engine. In early systems the filter was the most troublesome and crucial component technology since early gasifiers produced large quantities of entrained ash and tar particles that fouled the valves and scored the cylinder walls of the engines. This problem was completely overcome in later systems by a combination of three developments:

a) Development of gasifier designs that minimized the presence of tar and ash in the fuel gas produced.

b) Development of filters that effectively removed tar and ash particles from the fuel gas before its use by the engine.

c) Specification and control of the acceptable range of fuel properties for a given gasifier design.

The importance of this problem should not be overlooked in any revival of mobile gasifier technology. However, it is likely that filters need not be a significant limiting technology if adequate attention is given to control of particulate generation in gasifier design and fuel properties, and to the optimum use of the wide variety of highly-effective modern washable and disposable filters.

2.5 Air Mixer (Gas Carburetor) and Controls

The interface between the fuel gas generating system and the engine is the device for mixing secondary air with the fuel gas. This can be a very simple device such as the Italian and British designs shown in Fig. 11 since the required ratio of secondary air flow to fuel gas flow tends to be constant at about 1.0-1.1, and mixing occurs readily at the turbulent junction of two gas streams. In the vast majority of installations, the mixture was regulated manually by the operator to give the best performance for driving conditions and state of the gasifier fuel bed.

Some mixers were used, however, which automatically maintained a constant flow ratio under these conditions, e.g. Fig. 12. A smaller degree of manual control was still necessary, however, to compensate for the changes in fuel gas composition with time and driving conditions. It seems very likely, however, that with the present commercially-available gas composition sensors and state-of-the-art electronic controls, fast response and fully automatic maintenance of the optimum mixture ratio is practically obtainable.

2.6 Starting and Bi-Fuel Auxiliaries

Some mobile gasifier installations could operate entirely without gasoline. In these an air blower, either hand-cranked or more typically

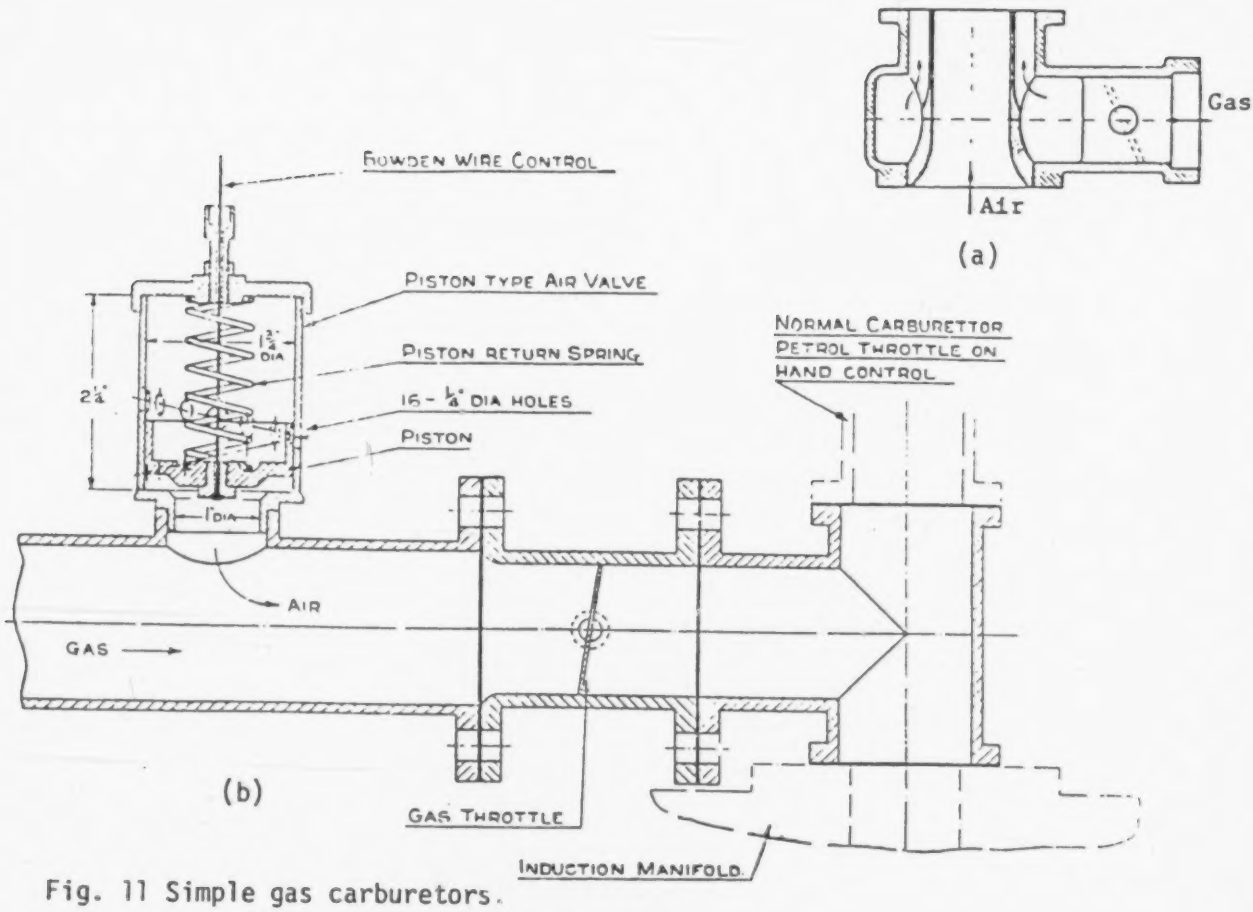

Fig. 11 Simple gas carburetors.

(a) Italian fixed mixture ratio.

(b) British driver-adjustable mixture ratio (used with government-designed producer).

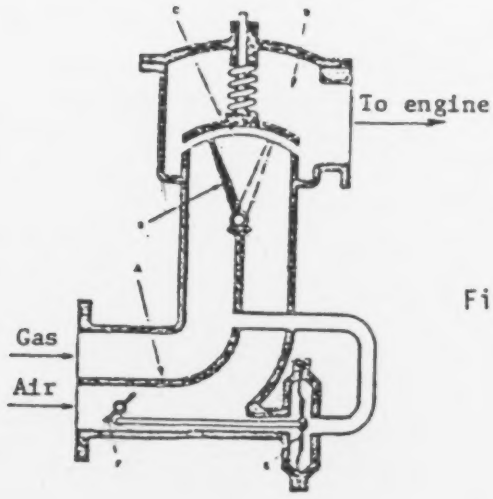

Fig. 12 Swedish automatic mixer maintaining constant ratio.

powered by an electric motor, was used initially to draw air through the system as in Fig. 4. A special starting match, similar to a miniature road flare, was ignited and inserted into the hearth region through the tuyere. When the blower exhaust could be ignited, after 2-4 minutes for single tuyere types and 4-5 minutes for others, the engine could be started. Although the vehicle could be driven immediately, full power was not developed for about 20 minutes initially. Thereafter, the engine could be restarted immediately without the blower if it had not been shut off for more than about ½ hour. For longer engine-off periods up to an hour, the blower would be used with no match and the engine could be started after less than a minute of blower operation.

Other installations retained the gasoline carburetor in the system and used no blower, as shown in Fig. 5. In such systems the engine was started on gasoline and the engine intake used to draw air through the gasifier. After the match was inserted, the vehicle could be driven immediately if necessary and switched by the driver to full operation on producer gas after a few minutes of operation. This bifuel type of installation also had the advantage that rapid transfer back to partial or full gasoline operation was available for exceptional conditions: e.g. for full power on very steep hills or rapid acceleration, and after exhaustion of coal supply or other failure of the gasifier system.

2.7 Fuels

Practical mobile gasifier systems have been operated with a wide variety of fuels (see Fig. 3). The desirable properties of mobile gasifier fuels are:

a) High heating value (to yield gas which maximizes engine output power and minimizes the weight and volume of fuel carried).

b) High reactivity/volatility (for easy starting and fast response).

c) Low tar production (to minimize corrosion and pollutant emission).

d) Low ash content (to minimize gasifier and filter design requirements).

e) Low sulfur content (to minimize gasifier and filter design requirements).

f) Non-caking and non-swelling (to avoid bridging).

g) Optimum particle size (to minimize pressure drop and hearth volume).

h) Low initial and pretreatment cost.

Unfortunately, several of these desirable properties tend to be mutually exclusive. Table 1 compares the composition, reactivity and typical heating values for several fuels on both a weight and bulk volume basis.

Table 1 Comparative Properties of Fuels

Fuel	Kcal/Kg	$Mcal/m^3$	% Ash	% Volatiles	% Sulfur	Reactivity#
Gasoline	11,000	8,500	-	-	-	
Wood	3,700	1,300	≤1		≪1	
Charcoal	7,000	1,400	≤1	10	≪1	.003
Peat	3,400	1,100	1-10			
Lignite	4,800	3,600	5-15	25-30	≪1 to 3	<.01
Bituminous	6,000-8,000	5,400	5-15	20-40	≪1 to 4	<.005
Semicoke*	7,000	2,800	3	12		.018
Coke	6,700	3,200	5-15	2-5	<1	.070
Anthracite	7,400	6,600	5-10	2-10	<1	.035

*British "Suncoal"

#CAB value; see Ref. 1, page 58 (high CAB indicates low reactivity.)

Among all fuels, coal is the most attractive on the basis of its abundance and its high heat content per unit weight, per unit volume and per unit cost. High volatile bituminous coals also are highly reactive for easy starting and rapid response to load changes, but cannot be used directly in most gasifiers because they produce large amounts of tar and tend to swell and cake. Hardwood and charcoal were the most widely used fuels, because they were readily available without wartime transport in many locations, and they functioned well in the early gasifier designs because of their high reactivity and their lower tar and ash content than soft woods and bituminous coal.

The record shows, however, that both gasifiers and fuels can be modified to match fuel supply and demand. The British, for example[4], initially used anthracite coal by developing a single-tuyere gasifier that

could function satisfactorily with this relatively low-reactivity fuel. The demand eventually outran their supply of anthracite, however, and they developed a low-temperature coking process that allowed conversion of the their abundant supply of bituminous coal into an adequately reactive and tar-free coke ("Suncoal").

Similarly, Sweden and France initially used charcoal almost exclusively, which places the least demands on gasifier technology. As fuel demand began to outrun the wood supply, however, the price of charcoal rose rapidly, and eventually the production of charcoal gasifiers was banned, causing direct wood-fueled gasifiers to become commercially dominant[1]. This dropped the per-mile cost of fuel by 40%, and greatly extended the wood supply since three times as much wood is required to produce the charcoal for a vehicle-mile than for the same vehicle-mile using the wood directly as gasifier fuel.

Gasifier and fuel processing technology also advanced to overcome other supply limitations. For example, crushing of coal and charcoal to obtain the optimum size resulted in the production of large amounts of unusable fines. This problem was met by pelletizing the fines and by development of gasifier systems specifically able to use fines (e.g., the highly successful Swedish Kalle system, Fig. 9(b), which recirculated entrained fines).

Fuel technology and the history of the availability and conversion of fuel supplies in World War II are documented in substantial detail in the literature. In particular, Reference 4 is a comprehensive post-war review of the British wartime experience with coal-based mobile gasifier fuels, and Reference 1 includes a comprehensive postwar review of the Swedish wartime experience with wood-based fuels. Reference 18 includes an extensive recent review of all fuels, including a wide range of biomass fuels.

Perhaps the greatest use of mobile gasifiers was in Germany during World War II [8,17,26]. Germany began the war with modest use of wood and charcoal fueled gasifiers. After 1942, however, use of coal-fueled gasifiers was greatly expanded for operation of a major part of the military transport

fleet. Unfortunately, very little literature describing this German wartime technology, production and use survived after the war.

2.8 Engine Adaptation to Mobile Gasifiers

No report has been found of an engine originally designed for use in a mobile gasifier system. Because of the suitability of producer gas for direct use in conventional internal combustion engines, all appliciations reported have involved either unmodified or modified conventional engines retrofitted with producer gas carburetors. A wide variety of engine types (listed in Fig. 3), in the power range of 10 to 200 horsepower, have been so employed, although there is no known inherent limit to size and type.

Generally, the power produced by a spark ignition engine operating on producer gas is less than 60-70% of the power of the same engine operating on gasoline at the same RPM and displacement. Diesel-type engines adapted to producer gas operation developed more than 80% of their rated power. A substantial part of this power reduction can be recovered in retrofit installations by increasing the compression ratio of the engine (modifying the cylinder head or cylinders), by modifying the intake manifold, by increasing the axle gear ratio by ∿10%, by adjusting the automatic transmission to shift at a higher RPM, or by installing a supercharger (a 6 psi supercharger makes producer gas equal to gasoline).

It should be understood however, that in the great majority of present U.S. vehicles, no modification of the engine or drive train would be necessary to allow the vehicle to accomplish its primary intended function using a mobile gas generator. Modern cars are overpowered by the 1940's standards. The maximum attainable speed and acceleration of the unmodified solid-fueled vehicle would be reduced, and it would spend longer time in the lower gears. Maximum speed and acceleration represent only a very small proportion of vehicle operation time, however, and operator adjustment to the reduced capability is no more demanding than adjustment to the much larger variation in these capabilities among presently-marketed vehicle models. Also, it should be clear that an engine and drive train designed initially for optimum operation with a mobile gasifier would be only a little more

costly and larger than that of present liquid-fueled systems to give comparable performance.

The technology of gasifier use with various types of engines is summarized in References 1, 18 and 25.

2.9 Vehicle Performance

It is convenient to note that about 12 lb of most mobile gasifier solid fuels (21 lb for wood) is equivalent to one gallon of gasoline on a miles-per-gallon basis. Since gasoline weighs about 6.2 lb/gallon, the additional average fuel weight between refuelings is about 50-100 lb which, together with the typical 300 lb weight of the gasifier system, amounts to less than 10% of the weight of a six-passenger car, or about equivalent to two additional passengers (proportionately less for smaller cars with smaller gasifiers).

The two-fold larger volume of coal compared with gasoline, and the six-fold larger volume of wood or charcoal, require either a significant increase in the total volume of the vehicle, or a substantial reduction in its refueling range. In practice the amount of fuel carried is a compromise between these alternatives. Use of densified biomass, which is 2-3 times as dense as wood, can substantially eliminate the volume disadvantage of wood and other biomass.

2.10 Emissions and Hazards

In normal operation of a mobile gasifier system, only the engine exhaust emission need be considered since the entire system is under negative pressure and cannot leak gas to the atmosphere. For a period after the engine is stopped, however, the gasifier continues to generate "blow-back" gas that exhausts from the air intakes. The concern about such emissions was treated with the traditional degree of attention given to the toxicity of CO in all internal combustion engine exhausts; e.g., caution was taken that the vehicle not be put into a garage until the gasifier had totally cooled. Modern concern with even transient emissions probably would require use of a

small flue with a catalyst that would ensure combustion of the blow-back gases.

Engine exhaust and emission of pollutants generally were not quantitative public concerns in the World War II era, so no data from that era exist which allow assessment of this presently-significant factor. Only two sets of data have been found relative to emission of pollutants from engines fueled with producer gas. Table 2 shows the pollutants measured in the exhaust of a 1965 Pontiac for both gasoline and charcoal-fueled producer gas operation over the standard EPA urban cycle[20,25]. Fig. 13 shows a comparison of the emissions from a 14 HP diesel engine for both diesel fuel and wood-fueled producer gas operation as a function of engine torque[18]. Both data sets indicate that the pollutant emission from engines operating on producer gas is comparable to that for operation on their normal liquid fuels. In neither case were the engines designed to minimize pollutant formation, and no attempt was made to suppress the emissions by adjustment of engine operation (e.g., fuel-air ratio) or by use of a catalytic converter as in modern vehicles. There is no a priori reason to believe that application of such pollutant suppression technology cannot similarly be applied to producer-gas engines, but this must be determined by actual engineering and tests of such systems.

It can be expected that the amount of pollutants will be strongly dependent on fuel composition, especially relative to emission of compounds of sulfur and nitrogen that exist as impurity compounds in the fuel. Such impurities are presently controlled in the production of liquid fuels before they are delivered to the consumer, and this would be the most desirable approach for solid fuels. This may be more difficult to control for local use of indigenous fuels, however.

Part (10-20%) of the sulfur in the fuel is captured by the ash and filter, and the remainder appears primarily as SO_2, H_2S and COS in the gas. The proportion among these gases depends on the completeness of the gasification and on the amount of water present in the fuel and primary air[18]. There are no EPA standards for sulfur emission from vehicles, but the EPA standard for stationary fossil-fired steam generators limits sulfur

Table 2 Engine Exhaust Emissions for Car Operated on Charcoal-Fueled Producer Gas Compared with Emissions for Same Car Operated on Gasoline (1965 Pontiac Tempest sedan, 320 cubic inch displacement engine; EPA hot start urban cycle FTP-CVS-72). References 20 and 25).

	Emission (grams/mile)			
	NO_x	Hydrocarbons	CO	CO_2
Gasoline fueled test	1.18	7.96	141	621
Producer gas fueled test	3.21	9.37	79.4	655
Typical Emissions for 1965 car (EPA)	3.6	8.8	87.0	
1980 Federal Emission Standards	1.0	.41	9.0	

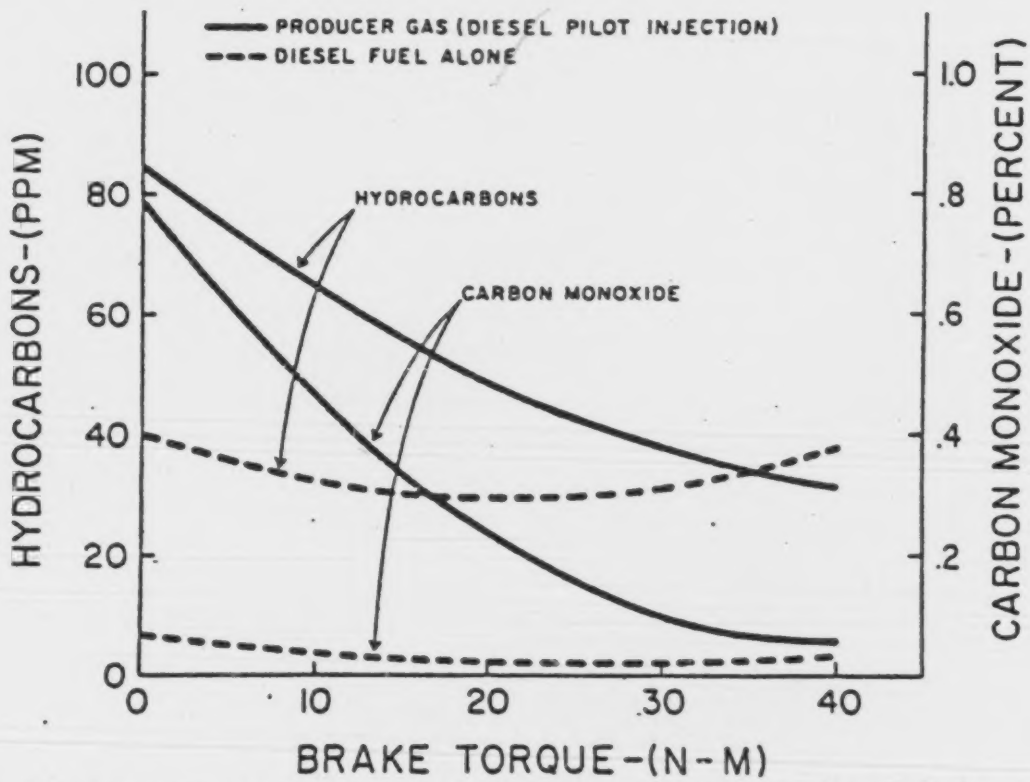

Fig. 13 Emissions from a 14 HP diesel engine operating on diesel fuel alone and on wood-fueled producer gas with pilot injection. Reference 18.

emission to less than 0.6 lb. of sulfur as SO_2 per million Btu in the fuel. This generally requires biomass fuels to contain less than about 0.1-0.2% sulfur which is generally true for all forms of wood, and most agriculture residues. For coal, however, the requirement corresponds to less than about 0.25-0.30% (0.15% for lignite). Large deposits of coal with such low sulfur content exist in the Western U.S., but most Eastern coal is in the 1-6% range. If indigenous coal fuels are to be used, therefore, means for preventing the sulfur release must be employed. Several commercially-practical methods for doing this exist. First, the sulfur in the coal can be substantially reduced by beneficiation and/or low temperature coking before it is burned[4]. Second, materials such as limestone powder can be added to the coal to capture a much larger part of the sulfur in the gasifier ash. Third, the sulfur can be extracted from the gas by a scrubber filter or by a recyclable charcoal bed[17] before it enters the engine, or can be similarly extracted from the engine exhaust gas. A study is required to determine which one or combination of the well-known methods is cost-effective for each gasifier-fuel combination.

In general, nitrogen compounds (e.g., NO_x) are produced in only insignificant amounts at the temperatures and high reducing conditions of the basic gasifier reaction. Nitrogen compounds in the fuel, however, can be converted into gases such as NH_3 and HCN. The only available data on nitrogen compounds in producer gas[18,22] suggests that only about 25% of the nitrogen in the fuel appears as these compuonds in the gas. There are no EPA standards for emission of these gases from vehicles, but the limit for oxides of nitrogen (NO_x) is 1.0 gram/mile. If this same limit is applied to 25% conversion of the fuel nitrogen into other nitrogen compounds in the gas, this limit corresponds to approximately a 1% nitrogen limit in wood and other biomass fuels, or 2% in coal. In general, most naturally-occurring fuels do not exceed these limits[18]. It seems likely, therefore, that the emission of nitrogen compounds for gasifier-equipped vehicles is no more significant than the NO_x emission normally occurring in the exhaust of internal combustion engines.

Because of the nearly complete absence of hydrocarbons in producer gas, it seems highly likely that emission of hydrocarbons and particulates from

gasifier-equipped vehicles is completely negligible compared with that from liquid-hydrocarbon-fueled vehicles. (The hydrocarbon emission for the charcoal-fueled vehicle in Table 2 almost certainly arises from leakage of lubrication oil past the pistons of the old engine tested).

In summary, therefore, it appears that pollutant emission during normal operation of gasifier-equipped vehicles can be controlled by the same means as with liquid-hydrocarbon-fueled vehicles if the relatively-abundant low-sulfur fuels (<.25%) are used. Furthermore, there are well-known means for using fuels with higher sulfur content in the gasifiers, and abnormal emissions (e.g., during startup) are certainly supressible by engineering design. It is, therefore, primarily a question of whether it is more cost-effective in some regions of the country to import low-sulfur fuels or to incorporate these means in the gasifier system. In view of the lack of meaningful pollutant emission test data for various fuels and gasifier types, the lack of specific regulations governing the various emissions, the lack of data relative to the supply and demand for low sulfur gasifier fuels in various parts of the country, and the absence of cost data for the sulfur-suppressing means and for low-sulfur fuels in various points of the country, it is not possible to credibly assess the impact of pollution emissions within the scope of this evaluation. It seems likely, however, that a more detailed evaluation would show that this consideration need not significantly affect the rate or degree of market penetration if reasonably adequate plans and preparations are made to minimize the pollution problem.

Explosion of the system apparently is not a significant hazard because of the low energy and high nitrogen content of producer gas. Except for a temporary increase in vehicle fires during the first year of large-scale introduction of mobile gasifiers in Sweden, apparently arising from inadequacies in early gasifier designs and inexperience in their use, no significant difference in vehicle fire or accident rates occurred there for vehicles with gasifiers[1].

2.11 Installation on the Vehicle

In the mobile gasifier system, the size of the gasifier itself is the quantitative factor dominating integration into the vehicle, together with its associated thermal and access constraints. The volume of the gasifier is determined largely by the volume of fuel required for adequate driving range. Its configuration is dominated by the requirement for gravity flow of the solid fuel (vertical cylinder), and optimum diameter of the combustion region (hearth) at its bottom.

Most mobile gasifiers evolved into vertical circular cylinders with height about three times the diameter. Also, the height of the hearth region averaged about 1/3 the total height. Combining these approximations with the fuel consumption rates quoted above, the trade-offs among the factors determining gasifier size are summarized by the relation:

$$H = 3D = K(WRfv)^{1/3}$$

where

K = 14 for metric units

= 6.2 for English units ( )

D = producer diameter in cm (inches)

H = producer height in cm (inches)

W = loaded vehicle weight in metric tons (tons)

R = loaded vehicle range in kilometers (miles)

f = fuel type factor

= 1 for coal, 2 for coke, 4 for wood and charcoal

v = vehicle type factor

= 1 for passenger cars, 1/2 for trucks and buses.

For example, for a 300 mile range, the above relation gives a coal-fueled gasifier 16 inches in diameter by 48 inches high for a 3000 lb 4-passenger (compact) car, and 17½ inch diameter by 52 inch high for a 4000 lb

6-passenger (full-size) car. The same size gasifier would give a range of 150 miles for coke as fuel, and 75 miles for wood or charcoal (which is still adequate for commuting).

In the World War II era, typical gasifiers for trucks ranged from about 46 cm diameter for a 5 liter engine to about 65 cm diameter for a 10 liter engine. Gasifiers for pasenger cars tended to be in the 40-45 cm diameter range. Filters and coolers occupied nearly the same volume as the gasifier in early installations, but these components became much smaller in the later systems. Because of this smaller size and their less-constrained configuration, they are not a major problem in vehicle integration.

Many types of vehicle installations were used: front and rear bumper mounting, trailer mounting, and mid-vehicle (fender and rear-cab) mounting. Some bus installations completely enclosed the gasifier within the body shell. Dozens of examples of different car, truck, bus, tractor, rail and marine installations are shown in photographs especially in References 1, 3, 5, 8 and 25.

Because of the above-described constraints imposed by fuel volume and gravity flow, the size of the gasifier itself was not significantly reduced in the later systems. Recently, however, a system has been demonstrated experimentally which removes the constraints inherent to the above equation, and which permits conventional horizontal under-vehicle fuel storage and incorporation of the gasifier inside the engine compartment[11].

2.12 Reliability and Maintainability

Little discussion of the reliability of mobile gasifier systems appears in the literature. Most of what appears is related to failure of filters, and to obstruction of fuel flow in early mobile gasifiers by bridging or clinker formation. Later improvements in filter and gasifier design, and selection of suitable fuels, essentially eliminated these reliability problems. The reliability of the engine is essentially unaffected when operated on producer gas.

Because the gasifier system is inherently simple in construction and operation, and all its components are highly accessible, it is relatively easy to maintain. Both routine maintenance and repair by replacement of parts are relatively simple operations. They can be performed at home by the typical owner-driver or by a service station along with other routine vehicle services (e.g. cleaning or replacement of filters, tuyeres or hearth rings). Reliability is directly related to regular servicing.

Rapid evolution toward low maintenance designs occurred during the World War II era, so estimation of service and maintenance costs for the typical later designs is difficult since relatively little experience was accumulated with them. An average maintenance cost of mobile gasifier systems during this evolutionary period is estimated in Reference 1. However, since this estimate is for trucks, it represents a larger-than-average system. Based on the extensive experience and data in Reference 1, maintenance and repair of the gasifier system is estimated to be about 1½¢ per mile. The total cost of 3¢ per mile is a relatively small increment of the present ~20¢ per mile total cost of passenger car operation. It seems very likely that the cost for the most recent systems would be substantially less, making maintenance a minor consideration.

2.13 Costs

The resources available for this assessment do not permit making a detailed economic feasibility estimate of the modern use of producer gas engine systems. Some economic aspects were discussed briefly in the early French and British context circa 1941[3,5]. There is a detailed economic evaluation of the producer gas system, however, included in the 1950 summary of the Swedish experience[1]. The extensive economic data and analysis included in that summary are uniquely valuable as primary reference material and are likely to be a point of departure for any further economic evaluation.

Unfortunately, however, that evaluation is based on the economic conditions and customs immediately after World War II in Sweden, and is exclusively confined to the use of wood and charcoal as fuel rather than

coal. Although the technology of producer gas systems has not changed significantly in the interim, there have been near-revolutionary recent changes in the relative values of currency, in the costs of fuels and vehicles, and in vehicle and engine design and performance. This makes it difficult and risky to form ratios to account for all these factors, expecially since these factors even then were undergoing large and rapid relative adjustments during and immediately after the war. Nevertheless, a few economic estimates will be attempted based on this and other sources.

In Table 3, the total cost of operation of wood or charcoal-fueled producer gas systems in a variety of applications is summarized, including all costs over the lifetime of the vehicle. This total cost is compared with the total cost of operating the same vehicle on gasoline, computed on the same basis. It is concluded that the cost of operation is the same in both cases when the cost of gasoline is 0.62-0.58 kronor per liter (2.23-2.09 per gallon) for the average size truck driving 30,000-50,000 km (19,000-31,000 miles) per year, and 0.87 kronor per liter (3.13 per gallon) for the average size passenger car driving 15,000 km (9400 miles) per year, if the cost of the charcoal fuel is 0.30 kronor per kilogram.

To make this comparison with the present cost of gasoline in dollars for vehicles with coal-fueled producer gas systems, it is necessary to establish a relationship between the 1950 kronor and the 1983 dollar, and to replace the wartime retail price of car charcoal in Sweden with a reasonable estimate of the retail price of coal mass-marketed at present in the U.S. for vehicle use.

Relative to the kronor-dollar relationship, it is noted in Table 3 that the purchase price of a small Swedish passenger car was 4,250 kronor and that of the average size car was 6,500 kronor. Similarly, the cost of four tires was said to be 400 kronor for the small car and 500 kronor for the average size car. The average modern car includes many items which were formerly rarely used or unavailable, including mandated pollution and safety equipment, automatic controls (engine and transmission), air conditioning, etc., and includes a more powerful engine and associated stronger drive train (an "average" Ford then had a 60 or 85 horsepower engine). A reasonable (but

Table 3 COSTS FOR VARIOUS TYPES OF CARS (from Ref. 1)

Costs	Small Passenger Car in Private Use	Average Size Passenger Car in Private Use	Average Size Passenger Car in Commercial Service	Average Size Truck in Private Use	Average Size Truck in Commercial Service	Average Size Bus in Commercial Service
Purchase price net, car incl. tires . . . . . .kr	4,250	6,500	10,000	13,000	13,000	22,000
" " " " excl. " . . . . . "	3,850	6,000	9,350	11,250	11,250	20,000
" " " tires, one set . . . . . "	400	500	650	1,750	1,750	2,000
" " " gas generator, incl. mounting . . "	1,250	2,500	2,500	2,500	2,500	2,500
Interest rate . . . . . %	4	4	4	4	4	4
Average interest per year, car, incl. tires . . . . .kr	96	146	240	297	312	514
" " " " gas generator. . . . . "	34	67	67	67	67	67
Write-off time, car . . . . . years	8	8	5	7	5	6
" " " gas generator . . . . . "	3	3	3	3	3	3
Depreciation per year, car excl. tires. . . . . .kr	482	750	1,870	1,608	2,250	3,334
" " " gas generator. . . . . "	417	834	834	834	834	834
Average insurance value incl. gas generator . . . . . "	4,000	6,000	9,000	11,000	11,000	19,000
" " " excl. " " . . . . . "	3,000	5,000	8,000	10,000	10,000	18,000
Average insurance premium incl. " " . . . . . "	400	450	650	575	775	925
" " " excl. " " . . . . . "	375	425	625	550	750	900
Service weight, car, incl. gas generator. . . . . .kg	1,150	1,700	2,000	3,200	3,200	5,100
" " " excl. " " . . . . . "	1,000	1,500	1,800	2,900	2,900	4,600
Car tax incl. gas generator . . . . . .kr	92	162	204	464	464	722
" " excl. " " . . . . . "	64	134	176	410	410	642
Garage rent per year. . . . . "	250	300	300	400	400	500
Driving distance per year . . . . . 10 km	1,000	1,500	4,000	3,000	5,000	5,000
Fuel consumption per 10 km, gasoline. L	1.4	2.0	2.5	3.5	3.5	4.0
" " " " " charcoal. . . . . .kg	2.3	3.2	4.5	5.6	5.6	6.4
" " " " " " . . . . . .(hL)	(0.13)	(0.18)	(0.26)	(0.32)	(0.32)	(0.37)
" " " " " wood. . . . . .kg	4.2	5.9	8.4	10.4	10.4	12.0
" " " " " " . . . . . .(hL)	(0.13)	(0.18)	(0.26)	(0.32)	(0.32)	(0.37)
Fuel price, charcoal, per kg. . . . . .kr	0.30	0.30	0.30	0.30	0.30	0.30
" " " " (hL). . . . . "	(5.25)	(5.25)	(5.25)	(5.25)	(5.25)	(5.25)
" " wood " kg. . . . . "	0.10	0.10	0.10	0.10	0.10	0.10
" " " " (hL). . . . . "	(3.25)	(3.25)	(3.25)	(3.25)	(3.25)	(3.25)
Fuel cost per 10 km gasoline[b] . . . . . "	1.35	1.75	1.74	2.16	2.03	2.28
	1.08	1.38	1.23	1.52	1.39	1.56
" " " " " charcoal. . . . . "	0.69	0.96	1.35	1.68	1.68	1.92
" " " " " wood. . . . . "	0.42	0.59	0.84	1.04	1.04	1.20
" " " " " gasoline[b] . . . . . "	1,344	2,619	6,954	6,470	10,130	11,356
	1,074	2,064	4,914	4,550	6,930	7,756
" " " " " charcoal. . . . . "	690	1,440	5,400	5,040	8,400	9,600

Table 3 (continued)

Costs		Small Passenger Car in Private Use	Average Size Passenger Car in Private Use	Average Size Passenger Car in Commercial Service	Average Size Truck in Private Use	Average Size Truck in Commercial Service	Average Size Bus in Commercial Service
Fuel cost per 10 km wood	.kr	420	885	3,360	3,120	5,200	6,000
Oil, grease, etc., cost per year	"	75	100	275	200	350	350
Tires, one set, " " "	10 km	4,000	4,000	4,000	5,000	5,000	4,500
Tires cost incl. repairs per year	.kr	125	225	700	1,100	1,800	2,250
Repair, lubrication,etc., car per 10 km	ore[a]	20	25	25	30	30	40
Repair, service, gas generator per 10 km.	"	15	15	15	15	15	15
Repair, lubrication, etc., car per year	.kr	200	375	1,000	900	1,500	2,000
Repair, service, gas generator per year	"	150	225	600	450	750	750
Fixed costs per km, gasoline	ore[a]	12.7	11.7	8.1	10.9	8.3	11.8
" " " charcoal	"	17.8	18.1	10.5	14.2	10.2	13.8
" " " wood	"	17.8	18.1	10.5	14.2	10.2	13.8
" " year, gasoline	.kr	1,267	1,755	3,211	3,265	4,122	5,890
" " " charcoal	"	1,771	2,709	4,165	4,245	5,102	6,896
" " " wood	"	1,771	2,709	4,165	4,245	5,102	6,896
Variable costs per km, gasoline[b]	ore[a]	17.5	22.2	22.4	28.9	27.6	32.0
" " " charcoal	"	14.8	18.5	17.3	22.5	21.2	24.8
" " " wood	"	12.4	15.8	20.0	25.7	25.6	29.9
" " year, gasoline[b]	.kr	9.7	12.1	14.9	19.3	19.2	22.7
" " " charcoal	"	1,744	3,319	8,929	8,670	13,780	15,956
" " " wood	"	1,474	2,764	6,889	6,750	10,580	12,356
Total costs per km, gasoline[b]	ore[a]	1,240	2,365	7,975	7,690	12,800	14,950
" " " charcoal	"	970	1,810	5,935	5,770	9,600	11,350
" " " wood	"	30.2	33.9	30.5	39.9	35.8	43.7
" " year, gasoline[b]	.kr	22.7	30.2	25.4	33.5	29.4	36.5
" " " charcoal	"	30.2	33.9	30.5	39.9	35.8	43.7
" " " wood	"	27.5	30.2	25.4	33.5	29.4	36.5
Costs of charcoal gas operation are equivalent to a gasoline price per litre of	ore[a]	3,011	5,074	12,140	11,935	17,962	21,846
Costs of wood gas operation are equivalent to a gasoline price per litre of	"	2,741	4,519	10,100	10,015	14,702	18,246
		3,011	5,074	12,140	11,935	17,902	21,846
		2,741	4,519	10,100	10,015	14,702	18,246
		96.0	87.3	69.6	61.7	58.0	56.8
		77.2	68.8	49.2	43.4	39.6	38.8

[a] Ore = one hundreth of a kr.

[b] Where two figures are given for gasoline operation, the upper one is a comparison with charcoal gas operation and the lower one with wood gas operation. See the explanation above for how the costs for gasoline operation were calculated.

hardly defendable) assumption is that these items constitute about half of the cost of the modern car.

It is assumed that the 1950 Swedish "small car" is equivalent to the present U.S. subcompact, and that the present U.S. average size is now about the same as the average Swedish size in 1950 (which was smaller than the U.S. size then). The typical U.S. small car presently costs (purchase price, not sticker price) about $6000 and similarly the average price of the present average size U.S. car is about $9500. Taking 1/2 of these prices to adjust for the added items discussed above, gives the contemporary equivalent prices $3000 and $4700, which are 71% and 72% of the respective 1950 costs in kronor of the small and average Swedish cars.

A typical set of four tires presently costs about $140 for a subcompact and $200 for the average size car. This is 35% and 40% of the respective 1950 costs in kronor of tires for small and average size cars. The fact that the modern tire costs are relatively so low could arise from the fact that the modern use of synthetic rubber and automated production has a greater impact on tire price than their modern use in the remainder of the car. Nevertheless, this result tends to indicate that the true dollar/kronor ratio may be somewhat lower than the above ratio based on car price. Accordingly, the 1950 kronor will be taken as equivalent to $.60.*

Relative to the wartime retail cost of Swedish charcoal compared with a present retail cost of mass-maketed U.S. coal, there is now no mass retail market for coal or gasifier wood on which to base a comparison. It is necessary, therefore, to base the comparison on other granulated solids which are presently retailed in package sizes and quantities approaching that of a potential automotive solid fuel market. Salt is presently mass-marketed in 50 lb. bags or boxes at a variety of retail outlets, and the bulk density of

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*The official exchange rate was $.27 per kronor in 1933, $.23 in 1980, and is $.13 in 1983. Clearly, the official value, although giving more favorable costs for the gasifier, is an unreliable comparison basis for present purposes.

salt is about the same as that of coal. Evidently this size and weight is easily handled by the retail customers, and it is equivalent to the fuel mileage value of about 4 gallons of gasoline, i.e., similar to the conventional 5 gallon gasoline can used to refuel vehicles.

The retail cost of a 50 lb. bag or box or kiln-dried salt presently is about $1.80 or 3.6¢/lb. in the San Francisco area. The truckload cost of bulk kiln-dried salt from the supplier is about 1.8¢/lb. in the same area, which is about the same price of a rail carload of utility-grade coal in this area. A reasonable estimate of the retail cost of automotive coal fuel, marketed at the same retail outlets and sale volumes as salt, is about 3.6¢/lb. which, incidentally, corresponds to an equivalent automotive fuel price of about 45¢/gallon of gasoline or about $19/boe (boe=barrels of oil equivalent=5.5 MMBtu). Similarly, for a wood cost of $30-50 per dry ton ($12-20/boe), the use of wood as mobile gasifier fuel would correspond to 25-45¢ per gallon of gasoline on a miles/gallon basis. Taxes would add about 10¢/gallon equivalent to this, but taxes were not included in the Swedish fuel cost. This price could be significantly lower if the sales volume for automotive coal and wood became comparable to that of gasoline, and if they were marketed through service stations in addition to groceries, etc. Either price could be significantly higher if special processing is required for the coal or wood.

Using the estimated 0.60 dollar per kronor, and substituting the estimated 3.6¢/lb. cost of coal for the 0.3 kronor/kilogram (8.1¢/lb.) cost of charcoal fuel used in Table 3, the total cost of operating a coal-fueled producer gas vehicle equals that of the same vehicle operating a coal-fueled producer gas vehicle equals that of the same vehicle operating on gasoline when the cost of gasoline is $1.03-$.93 per gallon for trucks driving 20,000-30,000 miles/year, and $1.64-$1.46 per gallon for the average size passenger car driving 10,000-20,000 miles/year. This is to be compared with the present $1.30 price of gasoline in the U.S. It should be noted, however, that if the cost of the gasifier were amortized over the life of the car (e.g. 8 years) instead of over the 3-year period used in Table 3, the contribution of the fixed (original) cost of the gasifier would be proportionately less and would make the gasifier system cost effective for

low-mileage passenger cars at present gasoline prices. Also, the cost for wood-fueled operation would be 0-20% lower than that for coal. These results are similar to those obtained in the recent cost estimates in Reference 17.

In summary, based on the Swedish experience, the retrofit automotive producer gas system appears to be distinctly cost-effective presently in the U.S. for trucks and other vehicles which travel more than 20,000 miles per year, well within the uncertainties of the estimates. The low mileage retrofit coal-fueled producer gas passenger car ($\sim$10,000 miles per year), although presently cost-effective in Europe, presently is economically marginal in the U.S. within this uncertainty, but would become distinctly cost-effective for the expected increase in the price of gasoline during a petroleum shortfall.

To obtain a more credible evaluation, a detailed analysis using current U.S. costs is required. The above analysis based on Swedish experience, however, indicates that the result is much more sensitive to fixed costs, such as the original purchase price of the producer system, than it is to the cost of the fuel, especially relative to the low mileage vehicles where the cost-effectiveness is not yet clear. A more credible estimate, therefore, would require definition of a specific modern design on which to base material, manufacturing and marketing costs.

In this respect it is informative to note that the adjusted purchase price of the producer system (including installation) is, from Table 3, $750 for small cars and $1500 for average size cars and trucks. Although it may be difficult to substantially lower this cost for a separately capitalized, marketed and installed retrofit system, the inclusion of an integral producer gas system during original manufacture of the vehicle might add relatively little to the price of the vehicle.

3.0 COMMERCIALIZATION ASSESSMENT

3.1 Commercial Scale Design

Many designs of mobile gasifiers were commercially mass-produced immediately preceeding and during World War II (in Sweden alone the government certified 503 different designs from 53 different manufacturers). The large number of designs is indicative of the very rapid rate at which the technology evolved in that period. The most successful of these designs began to dominate the market by the end of the war, however. In Sweden, for example, by 1945 only nine designs had more than 1000 units in use out of a total of more than 100,000 then in use in that country, and 60% of the certified units then in use were of only two designs.

Of all these designs, however, none are known to be mass-manufactured at present anywhere in the world. In fact it is likely that no set of production drawings suitable for mass manufacture of mobile gasifiers exist anywhere in the U.S. since none were ever mass-produced here. Crude drawings suitable for the hobbyist are available from some sources (e.g., "Mother Earth"[14] and "Popular Mechanics" magazines).

It is likely, however, that a mobile gasifier industry can be created in the U.S. and mass-production and nationwide utilization of such units established in less than two years, because this is what actually occurred in almost every other industrialized nation during World War II. Indeed, the U.S. can plan and prepare for acceleration of commercial production of mobile gasifiers by using the experience of its initiation in these other countries.

In the totalitarian counties, Germany, USSR and Japan, mobile gasifiers were produced as part of the general war production effort, and primarily for military and civilian cargo transport. Few records of the history of their gasifier production programs survived the war and, in any event, there probably is little of relevance to a future peacetime and commercial U.S. production scenario.

The history of the initiation of the British and Swedish programs are well-documented, however[1-4]. Consideration of these two cases individually is very instructive for U.S. purposes for two principal reasons: First, Sweden emphasized the use of wood as fuel almost exclusively, and Britain emphasized the use of coal almost exclusively, so that factors distinguishing the initiation and mass utilization of mobile gasifiers with these different fuels can be defined. Specifically, since both fuels are abundant in different regions of the U.S., these real examples can be considered as microcosms for the use of the indigenous fuels in these U.S. regions. Second, the British approach was socialistic by nature, in response to its emergency wartime involvement, whereas Sweden, as a non-combatant, proceeded almost entirely via free enterprise. Either approach could be optimum for the U.S., depending on the circumstance during the next few years, and comparison of the British and Swedish experience defines the relative merits and problems of these two optional approaches.

In 1937, two years before the outbreak of the war, the governments of both Sweden and Britain appointed committees charged with the objective of planning for the mass use of solid-fueled mobile gasifiers as a replacement for the anticipated interruption of petroleum supplies. The historians[1,4,8] concur and emphasize that the preparations made by these committees were crucial and highly effective in the subsequent rapid implementation of mobile gasifier use.

The British Mines Department, at the request of the Minister for Coordination of Defense, formed the "Committee on the Emergency Conversion of Motor Vehicles to Producer Gas"[2]. After surveying and testing the available technology, the Committee concluded that the conversion to producer gas was technically and economically feasible, but that none of the then commercially-available mobile gasifier designs were suitable for use with their adequately-available indigenous fuel (coal), and that none were suitable for mass-production with the anticipated wartime manufacturing and materials resources. The Committee thereupon instituted development and testing of a new design that incorporated a combination of the best features of prior commercial designs, and that could be mass-produced from sheet metal stampings. This design, the "Government Emergency Producer" [Fig. 8(d)] was

sized to operate with trucks and buses since the use of private automobiles was strongly discouraged and limited in Britain during the war. The design was elegant in its simplicity and producibility.

Upon outbreak of the war, this design was produced for various public and private transport companies by six different manufacturers. The government provided drawings and instructions for production, a comprehensive handbook describing installation, operation and servicing the systems, and a 90-day warranty against defective manufacture.[11] In addition, the government provided tax and other incentives to encourage conversion to mobile gasifiers, modified vehicle laws which might have restricted their use, organized production and distribution of fuels, and conducted further research and development for improvement of both fuels and gasifier systems. Seven subsequent versions of the initial system that became known as the "Government Utility Producer"[15] were produced in which the gasifier itself was modified only slightly, but in which the filter and cooler were substantially modified, including use of preheat and water injection to extend the range of acceptable fuel properties and supplies. Data on the number of units produced are sparse, but about 10,000 were in use by 1943[19] to equip "a substantial proportion of road transport" in Britain.

In the early 1930's, the Swedish Parliament funded research on mobile gasifiers by the Swedish Academy of Engineering Sciences, appropriated a loan fund to subsidize private purchase of mobile gasifiers by automobile owners, and provided a 33% vehicle tax reduction as incentives for their use. In February, 1937, the Royal Ministry of National Defense formed the "Gas Generator Committee of 1937" to determine how the technology developed might be accelerated for military preparedness. In December, 1937, the Committee issued an interim report that indicated the feasibility of large scale and effective use of mobile gasifiers for petroleum replacement, and defined the required preparatory research. In their final report in July, 1939, just as the war broke out, the Committee work had defined a preliminary plan for accelerating the use of mobile gasifiers, and a technology base had been demonstrated by fabricating and testing 100 charcoal-fueled mobile gasifiers in practical use throughout the country. Thereupon a new "Government

Generator Gas Committee" was formed to prepare and execute a detailed plan for accelerating mass mobile gasifier use.

At this point the Swedish approach departs substantially from the British approach. Although the preceeding Swedish government-sponsored work had produced usable designs and basic design criteria, intensive development work was undertaken by private industry which began to produce and competitively market a wide variety of new proprietary designs. Because of their inherent simplicity, mobile gasifiers systems were designed and produced both by large industries (including an automobile manufacturer) and by hundreds of small metal fabricator shops and "backyard engineers."

Although this uncontrolled private production easily satisfied the rapidly-increasing demand and kept prices low, it also resulted in the production of designs which were of inferior quality, i.e., potentially dangerous both on and off the highway, damaging to the car engine, and submarginal in performance. In an emergency situation, the consumer simply had no experience on which to base a choice prior to the purchase, and the reputation and rapid acceptance of the mobile gasifier suffered accordingly.

In order to remedy this intolerable situation without destroying the many advantages of the free enterprise approach, the Swedish government arranged for the testing of generator designs and certification of those which met certain standards (similar to applicance certification by Underwriter Laboratories in the U.S.). Submission of systems for certification was not mandatory, but most systems were submitted because certification greatly boosted the sales of a system, and the manufacturer benefitted from expert feedback from the experienced testing group relative to remedying any deficiencies. By the end of the war, 53 manufacturers had obtained certification for 503 different types of gas generator systems in Sweden, although 20% of the systems in use were not certified.

Although it did not intervene directly in the marketplace as did the British government, the Swedish government provided substantial assistance to the manufacturers, distributors and purchasers of mobile gasifiers. This relationship has many parallels to the relationship of the U.S. and state

departments of agriculture to the agriculture business. Research projects were performed jointly with the mobile gasifier manufacturers, with strong feed-back from the actual experience in practical use. Government advisory bulletins were issued to both manufacturer and user with recommended manufacturing standards and installation, operating and maintenance procedures for various types of cars and gasifiers. Training courses were offered for drivers and mechanics, and certificates (non-mandatory) were issued upon successful conclusion. Advisory bulletins on fuel standards and on the supply and demand situation were distributed to the 4000 private fuel producers in Sweden. Government loans were available for purchase of government-certified units (loans up to 80% of purchase and installation cost; no payment for the first six months; one-tenth principal payment every four months at 3% interest rate until paid). The purchase of 1000 mobile gasifiers for government vehicles in 1939 at the onset of the acceleration period had a strong stimulating effect on industry and potential users. Tax exemption and relief from inhibiting vehicle regulations also were provided as incentives.

The success of the Swedish program is apparent in Fig. 1. In the three-month period, July-October 1940, 20% of the Swedish civilian motor fleet was converted to mobile gasifiers, and gasoline rationing was discontinued thereafter. Within six months 30% converted, reaching more than 40% within a year. It is informative to compare the more than 100,000 vehicles using mobile gasifiers in Sweden at the end of the war with the number of vehicles then using other replacement fuels: 240 using acetylene gas, 531 using coal gas or methane, 1,180 using electrical power, and 6,612 using various alternate liquid fuels (e.g., alcohol).

It should be noted that the percentages given in Fig. 1 refer to the number of currently registered vehicles. In 1939, Sweden had a total of about 250,000 registered vehicles. This total dropped abruptly after the petroleum shortfall in 1940, but recovered almost completely by the end of the war as gasifiers and other measures compensated for the petroleum and other shortages. The decrease in percent of cars with gasifiers after mid-1941 reflects a recovery in the total number of cars registered while the number with gasifiers was still rapidly increasing. Also, the rate of

conversions became limited in mid-1941 by other wartime shortages such as tires, replacement parts and lubricating oil[1].

Frequent use will be made of this extensive and relevant British and Swedish experience as a reference base for evaluating mobile gasifiers as a U.S. oil replacement technology.

3.2 Demonstrated Operability and Reliability

Previous experience has clearly shown that the reliability of the mobile gasifier can approach that of the remainder of the internal combustion powered vehicle. However, there is an initial period in which incompetent or untried designs and operators can cause reliability problems that can greatly impede the acceptance of mobile gasifiers. Adequate preparation can greatly reduce or eliminate this period, however.

Mobile gasifiers were routinely and satisfactorily accepted and operated by millions of persons of widely-varying backgrounds and skills. Modern automatic controls can reduce the operator attention and skill required at least to the same degree as they have reduced the attention and skill required for other vehicle functions since 1945 (e.g., automatic transmission, choke, timing, etc.).

Other than the unknown nature of gasifier-fueled vehicle emissions, the unknown necessity for compliance with emission standards, and the unassessed technical difficulties for meeting these standards, there are no known critical areas of this technology which need create bottlenecks, as demonstrated by its past successful mass use.

3.3 Materials Limitations

The most successful designs developed and widely used were constructed mostly of mild steel. No bottleneck in this most abundant of U.S. structural metals is likely, even in the most rapid expansion mode, as discussed later. Some early designs made heavy use of refractory ceramics and corrosion-resistant alloys. The most widely used later designs minimized the use of

these materials, retaining them only for relatively small components in the high temperature region (e.g., tuyere nozzles and hearth rings). Presumably modern U.S. designs also would minimize the use of expensive or scarce materials.

4.0 OIL REPLACEMENT POTENTIAL

4.1 Resource Limitations

Coal and biomass are among the most abundant and widely-distributed U.S. resources. In many areas of the U.S. where coal is not locally abundant, wood is an abundant indigenous resource. In farm areas, mobile gasifier fuels derived from agricultural residues can satisfy most of the fuel requirements for operation of farm machinery and irrigation pumps (as is true in California as a whole, for example).

4.2 Rapid Acceleration Scenario

A 3-4 MMb/d oil supply cutoff to the U.S., accompanied by a 15-20 MMb/d shortfall in the non-communist oil market, would greatly enhance implementation of mobile gasifier technology. A cost of 150-200 $/bbl would reduce the payback time of a mobile gasifier to less than a year for the one gal/day family car, and to less than a month for most commercial transport vehicles. Experience has shown that an abrupt unavailability of or rapid price increase in fuel leads to rapid conversion of road vehicles to mobile gasifiers. No international events that would inhibit implementation of the technology are apparent.

In many non-communist countries where such a high fuel cost would be totally unacceptable, there are abundant indigenous supplies of wood, agricultural residues or other biomass and mineral fuels (e.g., peat) usable in mobile gasifiers. Although the U.S. may have commitments to supply these countries with oil, the amount of oil they would require could be greatly reduced or eliminated by supplying them with mobile gasifiers, or by providing them with the technology to build their own gasifiers using indigenous labor and low technology manufacturing facilities. If they lack sufficient indigenous fuels, the U.S. could supply them with mobile gasifier coal fuel.

4.3 Production Capacity and Lead Time Requirements

There is no current significant use of mobile gasifiers in the U.S. Efforts to identify any plans to implement significant expansion of the technology in the U.S. have identified a few individuals, commercial organizations and government agencies with interest in the technology, but none with the mission or resources to initiate a significant program.

It is clear that the U.S. has the fuels and manufacturing capacity to produce and operate a quantity of mobile gasifiers that would replace a significant amount of oil. From the experience in other countries during World War II, it appears that manufacture of the gasifiers and provision of the fuels themselves never were the limiting factors in the non-totalitarian countries, even in those heavily burdened by wartime arms and raw material production. The major limiting factors were more related to the lead time required to stimulate demand for the available technology than to provision of its supply.

Four such demand-limiting factors can be identified. First, a technology base must be developed well before implementation, and plans made to stimulate its use. Second, manufacturers and the public must become aware of the availability of the mobile gasifier technology as an economically viable and convenient option to petroleum fuels. Third, manufacturers must gain confidence that a large market exists in order to make the required investment for manufacturing, inventory, distribution and sales. Fourth, potential buyers of mobile gasifier systems must gain confidence in the integrity of this wholly unfamiliar product before they will actually buy.

This process occurs spontaneously in a free economy, but it occurs iteratively over a long period of time for a wholly new product. The record clearly shows that prior planning to relieve each of these limiting factors can greatly accelerate the mass implementation. The challenge is to implement the technology rapidly enough to prevent the unavailability or high cost of petroleum from destroying the economy before the petroleum-replacing gasifiers can rescue it.

The corresponding actions taken by the governments in the most successful and rapid implementations were: First, the government instituted development of mobile gasifier technology that defined and demonstrated the manufacturing, fuels and other requirements for units that would match the resources and needs of that country. Concurrently, the nature and location of manufacturers, fuels and users of such units were determined, and plans were made to distribute the technology and to stimulate demand. This preparatory process typically took 1½ to 2 years. Second, the government made the public aware of the mobile gasifier option through publicity and through widespread demonstrations in contests and by using the units with government vehicles. Third, the government placed large initial orders for units to power its vehicles, and made clear its firm intention to support and subsidize mass use of mobile gasifiers. Fourth, the government certified or warranted the integrity of the units, and provided assistance and incentives for their purchase and continued use.

Given an equivalent degree of preparation for and interest in implementing the mobile gasifier option by the U.S. government, the wartime situation in Sweden can be used to estimate the degree of oil replacement and implementation time in the U.S. The comparision with Sweden is most pertinent because its experience is reported in the greatest detail, because it chose the free enterprise route most likely to be taken in the U.S., and because as a non-combatant its experience was not dominated by wartime national mobilization as in the other countries. Although Sweden is a small country (about twice the size and population of Minnesota), it can be considered to be a microcosm of a region in the U.S.; i.e. it had proportionally few motor vehicles to convert, but it also had proportionally fewer manufacturing resources, etc. In fact, the manufacture and distribution of generators and fuels were performed primarily at the local community level, as evidenced by the more than 64 different generator manufacturers and 4000 fuel producers in Sweden alone[1]. The microcosm concept, i.e. the local production of gasifiers and fuels, using local resources and capital to satisfy local needs, is valuable as a basis for implementation as well as for estimation and planning. The level of U.S. production at which the microcosm analogy should be valid is estimated in Appendix C to be more than 14 million gasifiers per year.

The U.S. usage of petroleum in mobile engines anticipated for 1985 is 8.0 MMb/day[12] and is assumed to represent about 100 million vehicles. Assuming that the U.S. begins preparations this year that are analogous to those begun by Sweden in 1937, an analogous mobile gasifier technology base and plans for its implementation could be completed by 1985. The data in Fig. 1 for the fraction of the Swedish civilian motor vehicle fleet converted to mobile gasifiers is assumed to be indicative of the initiation rate achievable in the U.S. after a petroleum shortfall. As shown in Appendix C, utilization of only about 20% of the appropriate segment of the U.S. production base could provide a production rate of about 20 million gasifiers per year.

Sweden's oil supply was not interrupted until the invasion of France in April 1940, and a near total embargo was imposed after the invasion of Norway three months later. April, 1940 therefore will be taken as the equivalent effective date of the onset of the 3-4 MMb/d oil supply cutoff to the U.S. in January 1985. A subsequent linear rate of increase of gasifier production to the maximum rate (14 million gasifiers per year U.S. equivalent) 4-months later is indicated by the analogy, and this rate of introduction is assumed to characterize all final rates.

Fig. 13 shows the oil replacement potential of mobile gasifiers after the January, 1985 petroleum shortfall according to three scenarios. In the first scenario, gasifiers are introduced at a rate such as to achieve the replacement of the shortfall over the 5-year period covered by the OTA study. This requires production of 10 million gasifiers per year at about $15-20 billion/year original cost to the users, and has negligible impact on the appropriate manufacturers of the systems (about 10% of capacity) and on the national economy (½% of the U.S. GNP).

In the second scenario, gasifiers are introduced at a rate (20 million/year) which absorbs all surplus production capacity (20%) of the appropriate manufacturers and which somewhat exceeds the equivalent rate of introduction in the Swedish microcosm analogy. The petroleum shortfall is completely replaced in 2-3 years, and nearly all of the mobile engines in the

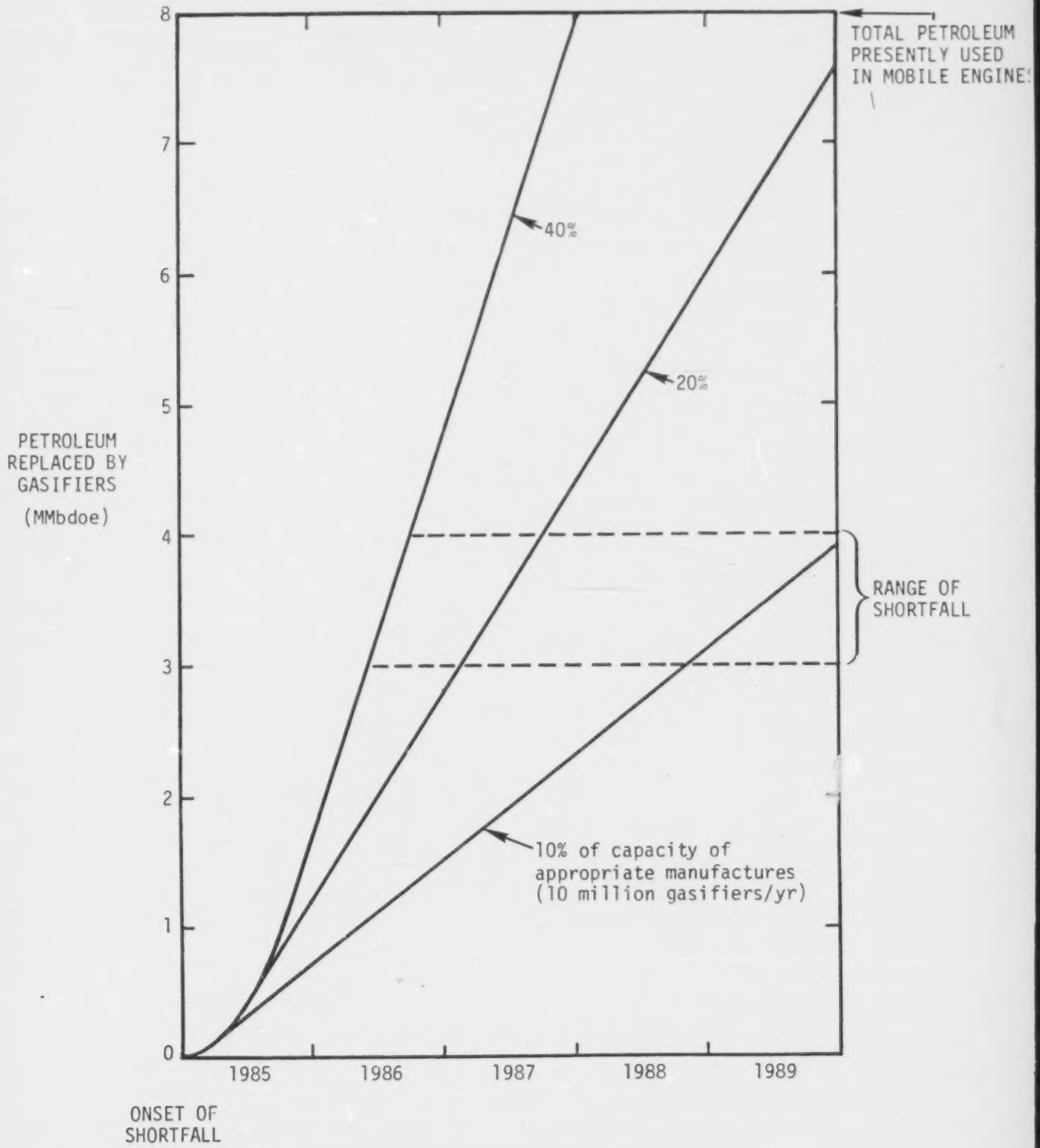

Fig. 13 Petroleum replacement by mobile gasifiers for three production scenarios.

U.S. could be converted to gasifiers within the 5-year period (replacing nearly 8 MMbdoe) if necessary.

The third scenario corresponds to a wartime-like mobilization of the affected industries to utilize a major part (40%) of their productive capacity to produce 40 million gasifiers/year, completely replacing the petroleum shortfall in about 1½ years and converting all mobile engines from petroleum usage within about 3 years.

Clearly, a great deal of detailed analysis is required to explore the rate and degree of conversion of each segment of the mobile engine fleet, and to verify the existence of material, manufacturing, fuel and distribution resources that such a conversion rate requires. It is just as clear, however, that implementation of mobile gasifier technology has a quite reasonable potential for replacing a significant fraction of the petroleum shortfall within much less than five years.

The potential very rapid rate of oil replacement by mobile gasifiers has significant implications. Given modest but adequate preparations, the shortfall might be significantly compensated by mobile gasifier use before exhaustion of reserves. This implies that rationing may be unnecessary during the transition, and that a smaller reserve may be adequate. Also, it implies that mobile gasifiers could be a flexible interim oil replacement technology while technologies requiring much longer times are implemented.

5.0 COST

The previously-cited cost estimate based on the detailed Swedish cost data gives the overall cost of mobile gasifier operation, on a miles per gallon basis, of 31-68 $/boe. Given the amount of relevant detail on the Swedish data, the principal uncertainty lies in establishing the 1983 dollar equivalent of the 1945 Swedish kronor. Other major uncertainties are the changes in relative cost of 1945 and 1983 technology, and the relative cost of Swedish and U.S. standards of vehicle use. Clearly an updated estimate based on current U.S. economics and a modern U.S. design is needed. It is unlikely, however, that such an estimate would be greatly outside the above-quoted range, or that a major oil price increase would have a significant effect on the estimate.

The capital cost is principally the purchase price to the consumer since the incremental capital cost to produce the gasifiers and fuel is negligible by comparison. Based on a purchase and installation cost of $1500, the capital cost is 63,000 $/boe/day per gallon/day consumed by the vehicle. Private passenger vehicles average near 2 gal/day (G&H Phase I estimate) for which the capital requirement for mobile gasifiers would be 32,000 $/boe/d. Commercial trucks and buses span the range of 4-40 gal/day, giving the capital requirement for mobile gasifiers as 16,000 - 1600 $/boe/d.

6.0 NON-INSTITUTIONAL CONSTRAINTS

6.1 Labor Availability and Materials Limitations

The weight of the mobile gasifiers is generally less than 10% of the vehicle it services. Assuming that the average weight of steel in each vehicle is 1½ tons, about 10 million tons of steel per year is used in vehicle manufacture in the U.S. Even if 40% of the total vehicle fleet were converted to gasifiers within one year, this would require less than about 0.4 million tons of steel for the gasifiers that year, which is less than .25% of the total U.S. steel output capacity.

Sheet steel, and steel tubing and pipe, account for approximately 50% of the total U.S. steel production. These are the principal steel forms from which a mobile gasifier would be fabricated, and the complexity of gasifier fabrication probably is near or below the average for all steel applications. Accordingly, the most-rapid scenario for construction of the gasifiers would involve less than ½% of the steel forms and, presumably, a similar negligibly small fraction of the associated U.S. steel fabrication, design, engineering, management, labor, and shop work force and facilities. It is likely, therefore, that the implementation of mobile gasifier technology would have no measurable effect on the total industrial base for producing this type of product.

6.2 Transportation Limitations

Because of the above-described small impact on the steel fabricating industry, the requirements for transporting the raw materials and steel forms, and for distributing the completed gasifiers, are felt to be negligibly small. The requirements of transporting the feedstock fuels for mass use of these gasifiers may be significant, however. OTA is familiar with feedstock availability and presumably will draw the appropriate conclusions.

6.3 Physical Constraints and Availability of Capital

Based on the Swedish experience, it appears that the response time of existing local enterprises to the manufacture of mobile gasifiers is much shorter than the time required to organize, capitalize, equip and otherwise initiate mass production facilities by large central industries, whether existing or new (e.g., the present several-year lead required to produce a new model car or to incorporate mandated pollution or safety devices.) Furthermore, it appears that the competition among these local enterprises is sufficiently intense to largely offset any cost advantages of central mass production. Production of gasifiers is more like manufacture of sheet metal stoves than like manufacture of automobiles or appliances.

In the early stages of accelerating the implementation of the technology, therefore, when government involvement should be most needed and effective, it is assumed that the microcosm (local-production-and-use) approach is the most time and cost effective. The engineering technology for a tested and proven system can be prepared in advance by the government: i.e. production drawings and instructions, bill of materials, production time estimates, installation instructions, operating and maintenance manuals. Local metal fabricators and system assemblers thereby can assess their ability to manufacture the mobile gasifier systems with their existing labor force and facilities, and to estimate the amount of additional (incremental) capital required to produce the systems. Provision of incremental capital for such new product ventures, through local banks, etc., is a routine part of American business. It is essential, however, that the manufacturers either have a sufficient backlog of orders or perceive sufficient future sales to realize an adequate return on this investment. For a rapid acceleration scenario, it will be necessary to provide a plan that assures market expectation sufficient to enlist that capital. Fortunately, the relatively small incremental capital required for production of gasifiers, and the short time for return on the investment, should be quite attractive to small investors.

After a stable mobile gasifier industry is established, including emergence of improved proprietary designs, government intervention will no

longer be required. The typical shake-out of sub-marginal manufacturers will occur, and the successful ones will merge or be acquired to reach the optimum size, location and financing of manufacturing facilities.

This production of mobile gasifiers in existing local facilities, with their established distribution and transportion networks, and using local capital, should tend to impose minimum physical and financial constraints during a crisis. In those localities with the greatest needs for the gasifier systems, the production of sufficient systems and fuels will have the greatest priority for the local physical and capital resources. Interest rates sufficiently high to dampen that priority will proportionally suppress all activities of that locality. With adequate planning to enable use of existing production resources that match local demand, investment costs can be negligible.

7.0 INSTITUTIONAL AND REGULATORY CONSTRAINTS

7.1 Regulatory Uncertainty

In countries that used mobile gasifiers, no major regulatory problems arose that could not be altered by modification or exemption. Regulations governing external attachment of devices to vehicles, use of trailer-mounted gasifiers with trucks and buses, restrictions on use of tunnels and bridges of external combustion vehicles, etc. are examples of the types of regulations that are encountered.

7.2 Environmental Regulations

Two areas of environmental regulations are especially uncertain. One is the extent to which vehicle and gasifier emissions will impact local and federal air quality regulations. As discussed previously, the amount and nature of vehicle emissions when operating on mobile gasifiers is largely unknown, and the extent to which any excessive emissions can be suppressed also is unknown. There is no a priori reason to believe that present regulations cannot be met by the application of conventional emission evaluation and suppression technology, however. For example, there is no regulation at present of sulfur emission from vehicle engines, although sulfur emission will occur for mobile gasifier systems if it is in the fuel. At present, sulfur in petroleum fuels is controlled at the refinery, and solid fuels could similarly be controlled at their source. Sulfur can be captured in the gasifier ash by including additives in the fuel, or can be scrubbed from the fuel gas or engine exhaust by a filter-combiner. Analysis and experimentation is required to define the most cost-effective approach.

Another area of environmental concern is ash disposal. The quantity and composition of ash depends on the nature of the fuel, and its physical form depends on the type of gasifier. For typical fuels, the quantity of ash is negligibly small, being equivalent in volume to an additional half or one gallon milk carton per household per week. There is no data on its toxicity. In high temperature (single-tuyere) gasifiers, however, the ash is typically fused into vitreous particles which are relatively non-reactive. Standards

and means for ash disposal must be developed concurrent with research that determines these factors.

7.3 Financial Incentives and Regulatory Relief

While it probably is not necessary for the government to capitalize the manufacture of mobile gasifiers, it is clear that government financial incentives to the user through low interest purchase loans, and through reduction of vehicle taxes, was highly effective in accelerating the implementation of mobile gasifier use in World War II. Once the basic cost-effectiveness of the technology was accepted by the public, the need for such incentives diminished greatly.

It appears to be essential, however, that all regulations which may inhibit use of mobile gasifiers are examined and modified to ensure that their effect is consistent with the importance of relief in a crisis situation. The U.S. is unique among the major industrialized countries of the world in that it has never dealt with the regulatory issues involved in the mass use of mobile gasifiers.

8.0 TECHNOLOGY UNKNOWN AND RISKS

8.1 Previously-Resolved Problem Areas (No Technical Risk)

The mobile gasifier system is unique among all solid-fueled automotive concepts in having already been thoroughly developed and tested over a period of a decade in about a million vehicles using coal, wood and other solid fuels. Accordingly, many initial technical problem areas have already been resolved in actual practice, and the related technology is well-described in the literature. There is no technical risk, therefore, in the production and use of the mobile gasifier systems which were practical and accepted in the World War II era. The following lists the problem areas which already have been resolved to that extent:

8.1.1 Basic Operation - The basic and engineering principles of mobile gasifier systems are sufficiently well-understood that practical systems can be designed and their performance predicted with a high degree of certainty. These principles have been thoroughly demonstrated in dozens of different designs for hundreds of millions of vehicle-hours of actual use.

8.1.2 Compatibility with Existing Engines - A wide variety of spark and compression ignition engines have been shown to be adaptable to producer gas operation, and their performance in such operation is well defined and understood. Engine fouling and increased wear in mobile gasifier systems was essentially eliminated in the latest systems developed.

8.1.3 Breadth of Applicability - Mobile gasifier systems have been practically employed in virtually every type of vehicle, and in every area of internal combustion engine application except aircraft.

8.1.4 Public Acceptance - The degree of acceptance of mobile gasifier systems in the various areas of application, as a function of availability and cost of petroleum fuels, has been demonstrated in more than a dozen highly industrialized countries.

8.1.5 Fuels - Specification of the required fuel properties and means for their achievement has been established in practical mass-production and use for wood, charcoal, anthracite coal and coke.

8.1.6 Costs - The costs of mass manufacture, retrofit installation and use of mobile gasifier systems, and the costs of mass production and distribution of associated solid fuels, have been demonstrated to be economically viable in the civilian economy of industrial nations during a period of restricted availability of petroleum in modern times.

8.2 Unresolved Problem Areas

The technical risks in mobile gasifier systems are differential in nature; i.e., they are associated with the uncertainties in extrapolating the previous well-established technology and practice to include new requirements which are secondary to the primary problem areas listed above. These risks, therefore, are more akin to the risks involved in bringing a new model to a previously-demonstrated market than to introduction of an entirely new and untried technology. The following lists these new considerations:

8.2.1 Satisfaction of Modern Engine Requirements - Modern automotive engines are similar to World War II era engines, except that modern engines have higher performance and, in many cases, operate in conjunction with automatic controls and transmissions. The most severe new constraint, however, is the legal restriction of exhaust emissions. Performance and emission test data are needed for operation of modern engines on gas produced from U.S. fuels. These data, combined with the basic knowledge of producer, engine and emission control devices, should be used to define optimum modern operating conditions, and system controls should be developed to maintain these optimum conditions by the modern control technology used in the most recent liquid-fueled cars. In later phases of development, consideration should be given to the use of superchargers and other basic design improvements for incorporation in engines designed specifically for producer gas operation instead of retrofitting liquid-fueled engines.

8.2.2 Improvement of Gasifier Performance - Starting with the World War II technology base, modern materials, combustion technology, fuels and controls should be applied to improve mobile gasifier performance and utility.

8.2.3 Public Acceptance - Public standards of vehicle performance, utility and appearance have changed significantly since the World War II era. The improvements in engine performance described in 8.2.1 and 8.2.2 above should be directed toward conforming to these standards whenever possible rather than seeking only maximum efficiency or minimum cost. In particular, completely automatic operation and minimum servicing of the producer system should be sought in accordance with the major change in these considerations between 1945 vehicles and present vehicles.

8.2.4 Fuels - Performance and exhaust emission data are needed for a producer gas engine system operating on the various types of U.S. fuels that are sufficiently clean, adequately available and economically feasible.

8.2.5 Costs - A cost analysis should be performed using presently-available data and estimates for the use of mobile gasifiers in the modern U.S. road transportation system. This initial assessment can identify the most sensitive factors determining maximum cost-effectiveness and public acceptance for guiding the technical evaluation and demonstration. As test and design data on modern systems become available, the cost analysis should be updated to include them.

9.0 CURRENT RESEARCH

Dozens of private individuals and small firms in the U.S. have constructed and operated charcoal, wood and other biomass-fueled gasifiers that are essentially reproductions of World War II designs. Most of these are in the "hobby" category, although some offer units for sale on a custom made basis. None of these activities are known to be in the category of professional research.

Two professional engineering research projects on mobile gasifiers can be cited, however. One of these is the activity of the Swedish Volvo company that was described in a 1974 company brochure[7], and is rumored to be still active. Volvo has not responded to written inquiries, however, perhaps because they consider their technology to be proprietary information.

Another is the activity of Rasor Associates, Inc. in Sunnyvale, California. Rasor Associates, in addition to constructing and operating a trailer-mounted coal-fueled cross-draft mobile gasifier based on the British World War II design (Fig. 8d), has also demonstrated operation of a proprietary aspirated-fuel compact gasifier for mobile applications. This novel design removes many of the control, fuel quality and configurational constraints of previous mobile gasifiers by separating fuel storage and feed from the gasifier-reactor, which also permits the entire system to be mounted within the body shell of the vehicle. Further engineering research on this project has been formally proposed[13,23] but presently is unfunded.

A large number of research projects on stationary biomass and coal gasifiers exist. Eighty-four of these are catalogued and described in detail in a recent SERI report[24]. Almost all of these projects are for continuous industrial-scale gasifiers that are much larger than appropriate for mobile gasifiers, although a few fall in the range applicable to automotive engines. Much of the basic technology reviewed in this comprehensive report is pertinent to and useful for development and evaluation of mobile gasifiers, but no professional research project to apply it to mobile gasifiers has been found.

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III. IMPLEMENTATION SCENARIO

This section is, in effect, a directed summary of the foregoing discussion of the nature and history of the use of mobile gasifiers for petroleum replacement. There are many alternatives to the procedures, schedule and infrastructure by which this technology could be implemented in the U.S. for a future petroleum supply shortfall. The following illustrative U.S. scenario is one credible set of these alternatives based on a combination of the British and Swedish experience.

1.0 PRE-IMPLEMENTATION EVALUATION, PLANNING AND READINESS PREPARATION

The first and perhaps most significant element in a rational scenario is a program for preliminary assessment of needs, resources and problems of implementing mobile gasifier use in the U.S. and, prior to the onset of a crisis, to prepare an implementation plan. A detailed 24-month plan[13] is included as Appendix B for a government-sponsored preparatory program to:

1. evaluate in detail how and to what extent the solid fueled mobile gasifier can be utilized to counter the impact of an emergency petroleum shortfall in the United States,
2. define an appropriate plan for such emergency utilization, and
3. make the necessary preparations in as short a time and at the least cost possible under present circumstances.

The preparatory program proceeds in four interdependent phases with the following chronological objectives:

a) Within 6 months from start:

- detailed U.S. mobile gasifier implementation needs and capabilities are identified.
- a usable and easily-producible reference system is identified and available for immediate use.

b) Within 12 months:

- a preliminary emergency plan is available for mobile gasifier implementation.
- the reference system is thoroughly tested and modernized.

c) Within 18 months:

- a complete implementation plan is available for local production and distribution of certified mobile gasifiers and solid fuels.
- detailed manuals for the production, installation, operation and use of the reference system, developed during 10,000 vehicle-miles of road testing, are available for mass emergency distribution.

d) Within 24 months:

- experience is obtained in competitive quantity production and fleet testing of at least 30 reference systems during 50,000 vehicle-miles of testing.
- emergency readiness is provided by maintaining know-how, technology base, and public acceptance as a nucleus for rapid large-scale emergency response.

The total cost of this preparatory program is about $1.2 million, excluding the cost of the vehicle fleet tests which can be assigned in part to the operator of the fleet.

As pointed out in Appendix B, continued use and production of the developed gasifier system at a low pilot level after the preparatory program will be necessary to preserve the readiness of the technology. This will maintain a nucleus of people experienced in operating and servicing the system, and will progressively upgrade the technology base and engineering know-how, as a nucleus for rapid large-scale emergency response. If the technology is cost-effective, its subsequent commercialization by the private sector could provide this readiness maintenance.

The remainder of the scenario assumes that this preparatory program is performed in the 1983-1985 period, and that the fully-developed and tested reference system and implementation (mobilization) plans are available at the time of the 3-4 MMb/d cutoff of U.S. imported oil.

2.0 INITIATION

2.1 Mobile Gasifier Manufacturers and their Suppliers

Within one week of the activation of the implementation plan, the information package prepared by the preparatory program is printed and mailed to the prepared list of likely mobile gasifier manufacturers throughout the country. This package includes a description of the mobile gasifier and outlines the implementation plan. It also includes assembly plans for the model of the reference system that is appropriate for the fuels available in the manufacturer's microcosm region. Production engineering data is provided, such as the type of labor and production facilities required, and the man-hour requirements and materials costs for each major component. Estimates of the number of units that will be required in the manufacturer's region also are provided, based on the degree and expected duration of the shortfall. A competitive regional procurement by the government is announced for a quantity purchase of reference mobile gasifier systems for use on regional government vehicles.

Those manufacturers which respond as being interested in producing mobile gasifiers are sent a more complete information package including full production drawings and instructions, bill of materials and their local suppliers, detailed production time estimates, installation instructions, camera-ready masters for operating and maintenance manuals, and a recommended warranty form. These interested manufacturers are subsequently sent bulletins which update the production technology, availability of materials, regional market and total production estimates and other information useful in their financing and production planning, and in facilitating their arrangement with retail outlets and installers.

To reduce lead time, regional suppliers of materials and commercially-available components for the mobile gasifier systems are alerted to expect an estimated increase in demand for these specific material forms and components.

At the end of the first month, the qualified lowest bidders (several for each region) are selected and given authority to proceed with manufacturing the assigned number of complete gasifier systems.

The complete production package is also sent, upon request, to any private individual or business that may wish to produce the system for their own use.

2.2 Fuel Suppliers

Concurrently, fuel specification packages are sent to the prepared list of prospective regional fuel suppliers that outlines the implementation plan. Methods of fuel preparation and testing to meet the specification are described and the anticipated regional demand for the fuel is estimated. A competitive regional procurement of a quantity of the fuel suitable for the regionally-procured government vehicle gasifiers is announced, and selection of several regional suppliers is made within the first month.

2.3 Regional Governments

A description of the implementation plan is sent to all relevant local governments and regulatory agencies, alerting them to potential regulatory problem areas and their recommended resolution. Relaxation of air quality and other federal regulations are announced if necessary.

2.4 Purchasers

Previously-prepared releases are made immediately to the mass media, describing the mobile gasifier system and the implementation plan. Photographs and video tapes of a variety of vehicles operating with mobile gasifiers are provided. Media events are arranged, including operation of the gasifier powered vehicles by reporters, and interviews of the developers and routine users in various circumstances. An office is identified that can be contacted by mail or telephone to obtain more detailed literature on the use of the sytem and on its availability.

The announcement of the selection of the producers of the first government-procured units and their price is released to the media and is mailed to all previous contacts, with a list of the successful bidders and of all other companies that intend to produce units. This announcement also includes a description of government-guaranteed low-interest loans toward purchase and installation of mobile gasifiers, and of tax and other incentives for use of the systems.

3.0 GROWTH

3.1 Rate of Growth

The competitive government procurement of mobile gasifier units is the only really predictable and controllable element of growth in the use of the technology. The number procured and the period of procurement is adjusted to stimulate growth at the rate established to be optimum for different degrees of petroleum supply shortfall.

A less predictable and controllable element, but one which has a much more profound effect on the growth rate, is the availability and price of gasoline at the pump. If the availability drops gradually, and the price rises gradually, individuals and firms adjust their lifestyle and business practices to conform to these new realities. The switch to mobile gasifiers occurs just as gradually after the differential in cost or distortion of business and lifestyle becomes unacceptable.

If, as in the case of Sweden and other countries, gasoline suddenly becomes totally unavailable, or available only in unacceptably small rations and at unacceptably high prices, individuals and firms turn massively to the mobile gasifier option in an attempt to maintain lifestyle and business-as-usual with the only available option. Under these conditions, a maximum growth rate such as that cited in Section 4.3 can be obtained.

If government chooses to do so, therefore, it is possible, to adjust the transition to mobile gasifiers over a wide range of rates by regulating the price of gasoline and the availability of oil reserves.

3.2 Consumer Protection

Each locality (microcosm) has one or more certification centers. They are equipped with dynamometers, emission instrumentation and other equipment which permits evaluation and optimization of mobile gasifier systems. They may be the EPA testing centers or an existing chain of muffler-installation,

automatic transmission or tune-up service centers under contract with the government.

Manufacturers (large, small and individuals) at their option bring vehicles with mobile gasifiers of their own design to these centers where they are given a series of performance tests and other inspections which determine whether they conform to minimum standards. If they pass, the design can be advertised and sold as being government certified. If they fail, consultation is given at the center, or with other government experts to determine how to overcome the inadequacy.

Similarly, individual operators bring their vehicles to the certification center to determine whether their specific unit conforms to the warranted or certification standards, and for instruction in optimum operation of their units. Courses in the operation, maintenance and repair of mobile gasifier systems, with appropriate certificates of completion, are offered by these centers to persons making their living by operating or servicing vehicles with these systems.

The government maintains a research and development activity on mobile gasifiers, and uses the certification centers to gather data on basic deficiencies in actual mass use, and to test new components, fuels or systems in actual use.

It should be possible to terminate the certification centers after a mature mobile gasifier industry develops, and after the consumer achieves the level of sophistication and familiarity with these systems that is required to make informed decisions based on comparison in the marketplace.

4.0 ROUTINE USE OF MOBILE GASIFIER SYSTEMS

Within two years (1987) the use of mobile gasifier vehicles is routine. A few of the newest models of the gasifier system now dominate the market. Dealers have begun to assume many of the services supplied by the government certification centers which also are being converted to private operation. The price range for mobile gasifiers is between about $1000 and $2000 for automobiles. The difference in price primarily arises from the number of optional automatic controls incorporated in the units and on chrome trim, fairings and other styling features which improve the appearance of the deluxe models. Larger models for trucks cost about $500 more. A used gasifier market has already developed at about half the price of the new models.

The most popular units are mounted on the rear of the car, or are mounted on one-wheel trailers attached to the rear bumper, and supply the engine with fuel gas. No modification of the typical car and its engine is necessary except for insertion of a simple gas mixer between the engine and its original gasoline carburetor. The units can be installed by the owner, but any mechanic can install them in four hours for about $200.

Because of its availability, low price, and ease of conversion and use, the mobile gasifier again has been rapidly accepted by the public. The first to convert were owners of older large cars which gave insufficient mileage on the gas ration to allow the owners to go to work or otherwise sustain their income and essential obligations. Salesmen and others requiring long trips also converted their small cars early. Families with recreational vehicles (motor homes, etc.) need purchase only one trailer-mounted system since it is easily transferred from one vehicle to another. Since only minor modification of Diesel engines is required, the conversion of bus and truck fleets was able to maintain full services as the available petroleum supply diminished. Farms have converted most of their off-road mobile and stationary machinery to mobile gasifier operation with assistance by the state and federal agricultural extension services as planned. A significant number of rail locomotives and river barges have been converted to a specia]

large mobile gasifier developed and promoted by the Department of Transportation.

Engine performance is reduced when converted from gasoline to producer gas, but this is not significant for cars with automatic transmission except for reduced top speed and maximum acceleration. Part or all of the performance loss can be recovered by minor engine modification or addition of a supercharger. Diesel-powered vehicles lose little or no performance when converted to gasifier operation.

In most parts of the country, crushed coal or biomass pellets are used directly in the mobile gasifier. They are packaged and distributed in 60 lb. bags and cartons (equivalent to 5 gallons of gasoline) by the distributors of other mass-marketed granulated products such as dog food, salt and charcoal, and through the same retail outlets. Filling stations also stock the solid fuel cartridges. The consumer can safely store reserves of gasifier fuel for his car in his garage, and can safely carry large reserves in his recreational vehicle for long trips. The cost of the gasifier coal fuel is equivalent to 55¢ per gallon of gasoline (including taxes), and the typical owner recovers his investment in less than 20,000 miles (1-2 years) at present gasoline prices. In regions of the Northwest, Northeast and Southeast U.S., wood fuels are less costly than coal. Farms use mostly agricultural residues augmented by commercial wood and coal fuels in the off-seasons.

The user (or his filling station attendant) refuels his car by opening a door in the top of the unit and dropping in the fuel cartridges intact (he never sees the fuel). At the same time he removes and discards an ash filter cartridge similar to a sweeper bag. He starts his engine cold on gasoline and drives away immediately as usual. The gasifier ignites automatically and the engine switches to full operation on coal or wood within about two minutes. For short stops (less than 15 minutes), the engine restarts on producer gas immediately. The driving range between refueling is 200-300 miles for coal and 75-100 miles on wood or other biomass.

Detroit has announced the delivery this Fall of the first car models factory-equipped with solid-fueled mobile gasifiers. The system is entirely contained within the body shell of the car which is no larger than its gasoline-powered predecessors and only two hundred pounds heavier. No external features or mode of driver operation distinguish the gasifier-powered car from the gasoline powered car. The engine, engine controls and drive train of the solid-fueled mobile gasifiers. The system is entirely contained within the body shell of the car which is no larger than its gasoline-powered predecessors and only two hundred pounds heavier. No external features or mode of driver operation distinguish the gasifier-powered car from the gasoline powered car. The engine, engine controls and drive train of the solid-fueled car are designed for optimum operation on producer gas. The standard size producer gas engine is 20% heavier but has the same power as the gasoline engines in equivalent models. However, this year the low cost of solid fuel permits an optional higher-power engine to be offered in the solid-fueled models that restores car performance to the pre-1985 levels when gasoline also was abundant and affordable.

Conversion to solid fuels began with the 1985 petroleum supply interruption, but after the solid fuel distribution system was put in place and clean solid fuels were available, public acceptance and economic factors appear to assure the permanent use of mobile gasifier systems and steadily decreasing use of highly flammable and explosive liquid fuels in automobiles.

5.0 CONVERSION POLICY PERSPECTIVE

The solid-fueled mobile gasifier is an economically and socially-acceptable short-range alternative to petroleum fuels in an emergency shortfall. If adequate preparations are made by government, such as the program outlined in Appendix B, mobile gasifiers can be mass-produced quickly in an emergency by many large and small metal fabricators throughout the country, with relatively small and local capital investment. The mobile gasifier gives individual consumers, both people and businesses, a short-range alternative to meet their individual urgent needs with local fuels and locally-produced units rather than wait nonproductively for a country-wide centralized solution. Similarly, instead of waiting for an intermediate synfuel processing industry to be organized, capitalized and developed outside of their control, individual coal and other solid fuel suppliers can meet the urgent demand locally.

The mobile gasifier is a petroleum-replacement solution from the bottom-level infrastructure up, rather than from the top down. It completely by-passes the production and distribution infrastructure and the network of corporate influence and government controls that now dominate the petroleum and natural gas industries. That network was as much (or more) responsible for the past "energy crises" as was the OPEC-imposed or natural gas supply shortfalls. It reintroduces competition, both domestic and foreign, into the transportation fuel industry, by giving the individual consumer a choice in the marketplace that is independent of the petroleum supply. The very existence of such a demonstrated and viably-planned alternative may be the most effective insurance against future planned shortfalls.

APPENDIX A

ANNOTATED BIBLIOGRAPHY

TITLE: "Generator Gas: The Swedish Experience from 1939-1945."

AUTHOR(S): G. Lindmark, et.al.

SOURCE: Swedish Academy of Engineering, Stockholm, Sweden. English translation available from the National Technical Information Service, Springfield, VA 22161 as document SERI/SP-33-140; 329 pages.

DATE: 1950

ABSTRACT:

This is a comprehensive history and quantitative technical treatis, from basic fundamentals through practical application, of all aspects of the field of mobile producer gas systems as a substitute for petroleum fuels, with emphasis on the Swedish experience before and during World War II. Separately authored chapters are on the following topics: history, theory of operation, fuels, producer design, filters and coolers, vehicle mounting, engine modification, garaging service, practical operating experience, economics, and hazards. Includes 63 references, mostly Swedish and German.

FINDINGS AND CONCLUSIONS:

This report is the most complete and comprehensive publication on mobile producer gas systems in existence--a prime and definitive source. It is especially valuable because it describes in detail political, economic, marketing and other social factors in a free-enterprise society similar to the United States. Its major shortcoming for present purposes is that it deals only with wood and related fuels, completely excluding consideration of coal. Its conclusions strongly suggest that producer gas systems were entirely practical and that their use would have continued if petroleum-fuels had not become cheaper than wood fuels after the war.

TITLE: Report of the Committee on the Emergency Conversion of Motor Vehicles to Producer Gas

AUTHOR(S): Harold Hartley, et al. (British Mines Department)

SOURCE: His Majesty's Stationery Office, London (available through Library of Congress), 27 pages.

DATE: 1940

ABSTRACT:

The history and results of the British government program to convert road vehicles to operation on coal-fired producer gas at the beginning of World War II is briefly but adequately summarized. A government-designed cross-draft, trailer-mounted producer system is described, and initial problems and their solutions are discussed. Practical operating experience is summarized, including a comparison with gasoline operation. Suitable fuels are defined and their availability is discussed.

FINDINGS AND CONCLUSIONS:

This report is exceptionally valuable and pertinent since it concerns the use of coal in automotive producer gas systems. The government-designed system is elegant in its simplicity, producibility and ease of application. Performance is not well-documented quantitatively, but operating experience indicates it is equal or superior to more complex designs. The British experience documented here (e.g. see Table 3 in the present text), and the basic coal-fueled producer design described, is a good point of departure for future development of mobile coal-fueled producer gas engine systems.

TITLE: Producer Gas for Road Transport

AUTHOR(S): Brian Reed

SOURCE: The Railway Gazette, London (available through Library of Congress); 72 pages.

DATE: 1941

ABSTRACT:

The application of coal-fueled producer gas systems to British heavy road transport is reviewed with heavy emphasis on the user viewpoint and rather little discussion of basic or engineering technology. A running history of the wartime conversion of the bus and truck fleets to producer gas is given with many examples and illustrations of specific installations and specific operating experience relative to performance, costs and logistics. A number of specific coal-burning producer designs are briefly described qualitatively but with good illustrations. Specific test logs of bus operation on various coal fuels are given.

FINDINGS AND CONCLUSIONS:

It is difficult to obtain uniquely useful data or to reach general conclusions from this rather incoherent assemblage of specific examples. This article gives valuable insight, however, into the many-faceted practical problems of converting to and obtaining solid coal as an automotive fuel--regulatory, political, logistical, personnel training, business finances, load factors, scheduling, economics, taxes, etc.--and the pragmatic British response to these problems.

TITLE: "The Emergency Use of Producer Gas for Road Transport. The Work of the Fuel Research Station on Fuels and Performance."

AUTHORS: T. F. Hurley and A. Fitton

SOURCE: Journal of the Institute of Fuel, Vol. 21, pp. 283-298

DATE: August, 1948

ABSTRACT:

The evaluation and development of coal fuels for mobile producer systems carried out at a British government research station prior to 1946 is reviewed. The results of numerous road and bench tests on a commercial up-draft and a government cross-draft producer are presented, including fuel properties, producer gas properties and vehicle performance factors, leading to a rating of the fuels in four classes of acceptability. Fuels tested included several varieties each of anthracites, low-, medium-, and high-temperature cokes. Effects of ash, moisture, reactivity, volatile matter, additives, air preheat and water injection are reported in many detailed graphs and tables.

FINDINGS AND CONCLUSIONS

This is by far the most detailed description of coal producer fuels found in the literature and, with References 6 and 7, rounds out the complete British experience with coal-fueled producer systems. It is strongly oriented toward the coal fuels available in wartime Britain, but leads to several general conclusions: Few coal fuels are suitable for up-draft producers, but many types can fuel cross-draft producers. Most anthracites and low temperature cokes are acceptable fuels, but medium and high temperature cokes are unacceptable in normal operation. Additives (1% Na_2CO_3) and air preheat (~100°C) with water injection (20%) can make many otherwise unacceptable fuels acceptable, but do little to improve performance of good fuels.

TITLE: Les Gazogenes: Constitution, Functionnement, Usage

AUTHOR(S): Albert M. Touvy

SOURCE: Collection Baudry De Saunier, Ernest Flammarion, Editeur, 26 rue Racine, Paris (available through Library of Congress), 143 pages in French

DATE: 1943

ABSTRACT:

The automotive producer gas field is comprehensively reviewed with emphasis on French technology and wood and charcoal fuels. Producer fundamentals and fuel characteristics are discussed briefly with no historical context. The construction, mounting and qualitative operation of various types and designs of producer systems are extensively discussed, with description of each component, accessory and operating procedure in outstanding detail. No references.

FINDINGS AND CONCLUSIONS

This qualitative review adds little to the literature that is useful in assessing the technical feasibility of the automotive producer gas system. It gives the impression that the French technology matured early and that its subsequent elegance was achieved through nonessential complexity rather than through basic improvement and simplification. It is useful primarily as a source of innovative ideas.

TITLE: Untersuchen von Fahrzeuggeneratoren bei Weich- und Hartholzbetrieb

AUTHOR(S): Hans List (Prof., Technischen Hochschule, Graz, Austria)

SOURCE: Julius Springer, Vienna (available through Library of Congress); 56 pages in German.

DATE: 1940

ABSTRACT:

Extensive experimental data are reported on the bench operation of two types of down-draft producers using a softwood (pine) and a hardwood (beech) as fuel. The following properties were measured as a function of operating time for each kind of wood and each type of producer operating at full, one-half and one-quarter flow rates: gas composition (CO, H_2, CO_2, CH_4 and other hydrocarbons), heating value and thermal efficiency. Similarly measured as a function of flow rate were dust, tar and acid contents and temperatures before and after the filter, heating value, and pressure drops. Heating value, temperature and engine power were also determined during transient operation.

FINDINGS AND CONCLUSIONS:

Although these data were for wood fuels used in producer types unsuitable for coal, they represent the most complete data base available for producer operation. As such they are useful as a reference point for design of future comprehensive tests on coal when the basic differences in the types of fuels and producer design are taken into account. Operation on hardwood gave gas in the 145-155 Btu/scf region and thermal efficiencies in the 80-85% region over a wide variety of operating conditions.

TITLE: Description of Volvo Producer Gas System for Cars

AUTHOR(S): S. Sorensson

SOURCE: Volvo Company, Uppsala, Sweden; 31 pages in Swedish, 11 references.

DATE: 1974

ABSTRACT:

At the beginning the first page lists the important characteristics of the system; while it is suitable for engines with a stroke volume of 1.5 to 2.5 liters, it can be adapted for larger engines. The producer gas plant is a complete unit mounted on a pivot trailer. The conversion time for the Volvo 140 series is approximately 4 hours. The fuel is made up of wood chips from the cellulose industry packed in hundred liter paper bags, weighing approximately 20 kilograms. The gross laden weight increases about 140 kilograms, while the producer gas equipment weighs about 170 kilograms. The driving range for each fuel load is, for the Volvo 144, approximately 80 kilometers or just over an hour. In general, producer gas reduces engine output by approximately 50 percent. The rest of the document is technical information. Part 2 describes the principal chemical reactions occurring in the production of the gas, the different kinds of gas generators, and various kinds of cooling and cleaning systems. Part 3 describes the dimensions of the combustion chamber, and the temperature of the gas, which are displayed on several graphs.

FINDINGS AND CONCLUSIONS

This report has been requested from the Volvo Company in Sweden but has not yet been received. The data in the abstract are consistent with World War II wood-burning producer performance.

TITLE: The Pegasus Unit

AUTHOR(S): N. A. Skov and M. L. Papworth

SOURCE: Pegasus Publishers, Olympia, Washington; 133 pages

DATE: 1974

ABSTRACT:

This is a relatively recent review of producer gas systems using material from the Swedish review (reference 1) and from Danish and German wartime publications. The wartime history of the conversion to producer gas in Denmark is summarized, the basic producer processes and functioning of various producer regions and producer types is discussed, and the characteristics of various fuels are reviewed with emphasis on wood and charcoal, and only a few sentences on coal. Excellent illustrations of several German producer systems and numerous summary tables are given. 13 references.

FINDINGS AND CONCLUSIONS

This material is easily read, but it is largely third-hand information assembled from previous reviews with a strongly undergraduate pedagogical flavor. Because of its excellent illustrations and summary tables, it is useful for pedagogical purposes, but reference to the primary sources is recommended before any of its conclusions are accepted. (Incidentally, PEGASUS is an acronym coined exclusively by the authors for Petroleum/ Gasoline Substitute Systems.)

TITLE: Producer Gas Power 1974 - Producer Function and Installation

AUTHOR(S): ————

SOURCE: Motorbranchen Forlag Karlovaegen 14 A P.O. Box 5611 511486 Stockholm, Sweden; Vol. 35, No. 3, 5 pages in Swedish.

DATE: 1974

ABSTRACT:

A survey is given of the devices for producer gas systems to be used in road vehicles. The survey includes a review of the planning aspects for the production of these devices and the wood to be used in them. The technical function of the producer is described. The producer consists of a gas generator, filter cleaner, cooler and air mixer. These separate parts are described and their principal functions are outlined. Wood blocks or chips are used as fuel. Principles for connecting the producer to different types of engines and the changes necessary to adapt the engine to the producer are outlined. Engine power and fuel consumption are discussed. The decreased engine power is said to be 40-50% for carburetor engines and 10-30% for diesel engines. The fuel consumption is dealt with in three numerical examples. Different types of producers now available in Sweden are described as well as various installation possibilities for passenger cars, lorries, buses and tractors. Because of the risk of poisoning and fire, rigourous security rules concerning installation and handling are necessary.

FINDINGS AND CONCLUSIONS:

This article has been ordered from Sweden but has not yet been received.

TITLE: "Instruction Book for Government Utility Gas Producer (Marks VI and VII)."

AUTHORS: Ministry of War Transport (British)

SOURCE: Library of Congress (TL229, G3G72, 1943)

DATE: 1943

ABSTRACT:

This is a 32-page installation, operation, and maintenance manual for the circa 1943 models of the British government-designed mobile gasifier system. The table of contents and foreword are reproduced on the following page.

FINDINGS AND CONCLUSIONS:

This is the most highly-detailed description in the literature of the routine practical use of a specific mobile gasifier design. Highly detailed drawings and description of every component are given. All qualitative aspects of the system and of its use and maintenance are described in great practical detail for the hands-on layman. It is a gold mine of the minute details required to make a practical system work. It is the equivalent of a mechanics manual for a specific model of vehicle.

CONTENTS

Foreword ... ...

Producer Gas—What it is ...
How it is made

How the system works ... ...

Construction and layout ... ...

Fuel ... ...

Controls ... ...

How the controls work ... ...

Operation — Starting ... ...
Driving ... ...
Idling and waiting
Refuelling ...

Maintenance — After Running ...
Frost Precautions
Every 1,500 Miles
Every 4,500 Miles
Engine ... ...
Diagnosis of Faults

Dismantling Instructions ... ...

Hints for the Driver ... ...

What the Law Says ... ...

Appendix A—Area Fuel Organisers
Bulk Fuel Suppliers

FOREWORD

The Government UTILITY Gas Producer Unit described in this instruction book has been evolved by the Government and applied by five leading motor manufacturers. It embodies improvements suggested as a result of intensive trials carried out by some of the largest goods vehicle operators in the country, and it will do the work it is designed to do *if it is given proper attention.*

When converted to producer gas, an engine is not as efficient as when running on petrol. It does not develop the same power or provide the same liveliness. It requires a certain amount of additional attention from the driver and the maintenance staff. But it will play a vital part in conserving liquid fuel essential to the war effort, and for this reason alone it is up to every operator and driver to accept it in the right spirit and make sure that it does its job.

Producer gas is derived from fuel mined in this country. Liquid fuel—petrol and diesel oil—has to be brought across the seas, at grave risk to men and ships. The combined tanker resources of the United Nations are strained to the uttermost to meet the needs of the fighting services.

Everything that can be done, therefore, to relieve the strain on these resources is a direct contribution to the war effort. Every gallon of fuel saved is a gallon more to use against the enemy.

But there is another and more important reason for urging the full co-operation of the road transport industry. Road transport is vital to the continuance of the war and the life of the community. Road transport must and will be carried on. But the time may come when sufficient liquid fuel will not be available even for essential services. And if that time *does* come it will be necessary to operate a far more substantial percentage of road vehicles on producer gas.

The Government scheme has been deliberately framed with this possibility in view. The transition should it come, will be a big and difficult task, and road transport operators can smooth the way for the industry in advance by getting to know and understand the producer-gas plant *now*.

Every assistance has been promised by the motor manufacturers, and gas-producer service and repair facilities are being organised throughout the country. Bagged fuel for small operators is already available from the dealer of the motor manufacturer who is appointed to convert your vehicle. The names of other selected dealers can be obtained from the Area Fuel Organisers or from the designated bulk fuel suppliers who are listed on pages 30 and 31.

The Government Utility Producer is sold to operators under warranty and a copy of this warranty is included in Appendix B on page 32.

The Government, the motor manufacturers, and the motor dealers and repairers are going to do their utmost to run the scheme efficiently and smoothly. It *will* run efficiently if YOU, as an operator or a driver, play your part with the same keenness and goodwill.

TITLE: Vehicle Gas Producers

AUTHOR: Ernest E. Donath

SOURCE: Fuel Processing Technology, 3(1980)141

DATE: 1980

ABSTRACT:

This is a short review of mobile gasifier technology based on relatively few pre-1943 references, with a view toward applying this technology for modern conditions.

FINDINGS AND CONCLUSIONS:

There is relatively little information and data in this paper that cannot be obtained in other more comprehensive reviews. Some discussion of the limitation of pollutant emissions is included, however. Also, a somewhat detailed and useful discussion of the economics of gasifier-powered vehicles is included, based on current prices and usage. It is concluded that the "breakeven" prices of gasifier fuels, above which gasifier use would presently be cost effective compared with use of gasoline, are for 20,000 miles and 40,000 miles annual use respectively: for wood $42 and $53/ton; for brown coal char $75 and $95/ton; and for anthracite coal $87 and $110/ton.

TITLE: State of the Art for Small Scale (to 50 kW) Gas Producer-Engine Systems

AUTHORS: A. Kaupp and J. R. Goss

SOURCE: Final Report, U.S. Department of Agriculture Forest Service, Contract 53-319R-0-141 (University of California at Davis, Agricultural Engineering Department)

DATE: March 1981

ABSTRACT:

This report is an updated version of the 1950 Swedish summary (Ref. 1) in a very similar format with comprehensive chapters on history, chemistry, producers, fuel, gas conditioning, engines and economics. Although much of the technology reviewed is relevant to mobile gasifiers, emphasis is on systems for developing countries and small stationary systems are included. The survey is based on a review of 600 papers (most prior to 1950) which have been cataloged for computer access, and on 130 responses to over 400 international invitations to contribute to the report.

FINDINGS AND CONCLUSIONS:

This large report only recently has been released and has not been read completely for this bibliography. However, it appears to be a landmark publication for small-scale gasifier systems, with a high degree of thoroughness and competence. It is a valuable resource for data and references, especially for post-1950 work not available in the 1950 Swedish summary. It is not a replacement for the Swedish summary, however, since aspects of particular interest for the mobile application are omitted in favor of the stationary systems which are the primary objective of the authors and sponsor. For example, the economics section focuses almost exclusively on stationary systems using biomass for developing (Third World) countries. This orientation, and references to current prices for custom-made (one-at-a-time) systems, are not nearly as relevant to the circumstance of oil replacement by mass-produced mobile gasifiers as is the chapter on economics in the Swedish summary.

TITLE: Coal-Fueled Producer Gas Engine System

AUTHOR: N. S. Rasor

SOURCE: Report Prepared for California Energy Commision, Contract 500-79-119

DATE: September 1980

ABSTRACT:

The status of coal-fueled mobile gasifier technology is reviewed as part of the California Energy Commission (CEC) Clean Coal Project. Previous literature and activity existing as of 1980 are summarized relative to the objectives of the Project.

FINDINGS AND CONCLUSIONS:

This report is a condensation of material that can be found in the other publications of this bibliography. Although much of the material reviewed concerns wood and charcoal-fueled systems, emphasis is on the more limited information on coal-fueled systems. Much of the material in the OTA report is abstracted from this CEC report.

APPENDIX B

PREIMPLEMENTATION PROGRAM PLAN[13]

3.0 PROGRAM PLAN

3.1 PROGRAM OVERVIEW

3.1.1 Guidelines

Because the subject area of the proposed program is many-faceted, it is necessary to limit its scope and emphasis to those aspects presently perceived as being the most urgent and important, and as being consistent with the policy of the U.S. Department of Energy. Accordingly, the following guidelines will be followed in defining the proposed work, with the understanding that the proposal can be modified if necessary to reflect current DOE policy:

Time Frame - It is assumed that the emergency petroleum shortfall can occur at any time during the program as well as anytime after its completion. The program is structured, therefore, to define a usable preliminary reference system and preliminary plan for its use as early as possible. The reference system and plan are coherently upgraded such as to be useful in an emergency at any stage of development during the program, and to be maintained in readiness after completion of the program.

Central vs Local Execution - Emphasis is on using local private capital, facilities, labor and management to produce, distribute and market locally-available fuels and generators capable of satisfying local demand and needs. The Federal Government provides base technology, incentive, and modification of restrictive Federal regulations as needed, and establishes national standards for optional local certification of fuels and generators. At every opportunity during the program, consistent with available resources and adherence to schedule, contact is maintained with representative state and local agencies, and their inputs are considered.

Technology Level - The use of proven and currently-available technology is emphasized to make adequate and reliable generators and fuels available at the earliest possible date. Improvement of the reference system is undertaken only after the previously-established base technology is available for immediate use in the U.S.

Fuel Types - Solid fuels are emphasized initially which a survey shows to be abundantly available in the regions of the country which will be impacted most heavily in a petroleum shortfall, and in which the greatest and earliest petroleum replacement can be achieved, consistent with acceptable fuel quality and environmental impact. Subsequent emphasis is on fuels for successively less important regions.

Generator Types - Generator designs are emphasized which can utilize the types of solid fuels which have the greatest potential use in the U.S. A single reference design is sought which, with minimum modification or change in size, can be used with most U.S. solid fuel varieties and in most U.S. applications. Use of abundant non-strategic domestic materials of construction is emphasized.

Mode of Use - Emphasis is on emergency external retrofit of existing vehicles and installations. Early availability, minimum initial and operating costs, and high reliability through simplicity of construction and operation are emphasized initially rather than attractive appearance and automated convenience. Attention is given to these latter qualities, including possible integration into the vehicle, after the minimum but fully functional reference system is available.

Applications - Retrofit of road vehicles, including passenger cars, trucks and buses, is emphasized initially. Subsequent emphasis is on other applications in which the reference retrofit system so defined can be used also to sustitute local solid fuels for petroleum in large quantities, e.g. farm equipment, irrigation pumps, driers, industrial furnaces, space heaters, river transport, rail transport, etc.

TIME FRAME

AT 6 MONTHS: U.S. NEEDS IDENTIFIED AND USABLE SYSTEM AVAILABLE.

12 MONTHS: EMERGENCY PLAN AND TESTED MODERN SYSTEM AVAILABLE.

18 MONTHS: MOBILIZATION PLAN AND 10,000 VEHICLE-MILES OF TESTING.

24 MONTHS: 50,000 VEHICLE-MILES OF FLEET TESTING.

LOCAL EXECUTION

CAPITALIZED, MANAGED, PRODUCED, MARKETED, FUELED AND USED LOCALLY.

TECHNOLOGY

WORLD WAR II, OFF-THE-SHELF TECHNOLOGY BASE.

FUELS

LOCAL SOLID FUELS FOR MOST HEAVILY-IMPACTED REGIONS.

GENERATOR TYPES

BEST FOR U.S. FUELS AND U.S. USE.

MODE OF USE

RETROFIT.

APPLICATIONS

ROAD VEHICLES FIRST, THEN ADAPTATION TO OTHER USES.

Fig. B-1 Guideline Summary

3.1.2 Program Administration and Schedule

The program is conducted in four overlapping phases as shown in Fig. 3.1. The periods of overlap provide the degree and speed of iteration which is required for the program to proceed rapidly from inception to full readiness for response to an emergency petroleum shortfall. Such rapid progress is possible only because of the precident technologies and logistic base already established in other countries. It is necessary, however, to concurrently determine the unique current resources and requirements of the U.S., and to modify the previous base to suit these unique circumstances as the U.S. acquires its own technology base and emergency plan.

Phases I and III are survey and planning activities in which the data base for defining U.S. requirements and capabilities are acquired, and the logistics of a U.S. emergency plan are evolved. This portion of the program is performed primarily by Interdevelopment Corporation in conjunction with Rasor Associates as prime contractor.

Phases II and IV are engineering evaluation and development activities in which a reference system is developed, and performance standards and practical operating experience are obtained, as the technology base for the U.S. emergency plan. This portion of the program will be performed by Rasor Associates and iteratively maintained consistent with the requirements and plan developed by Interdevelopment.

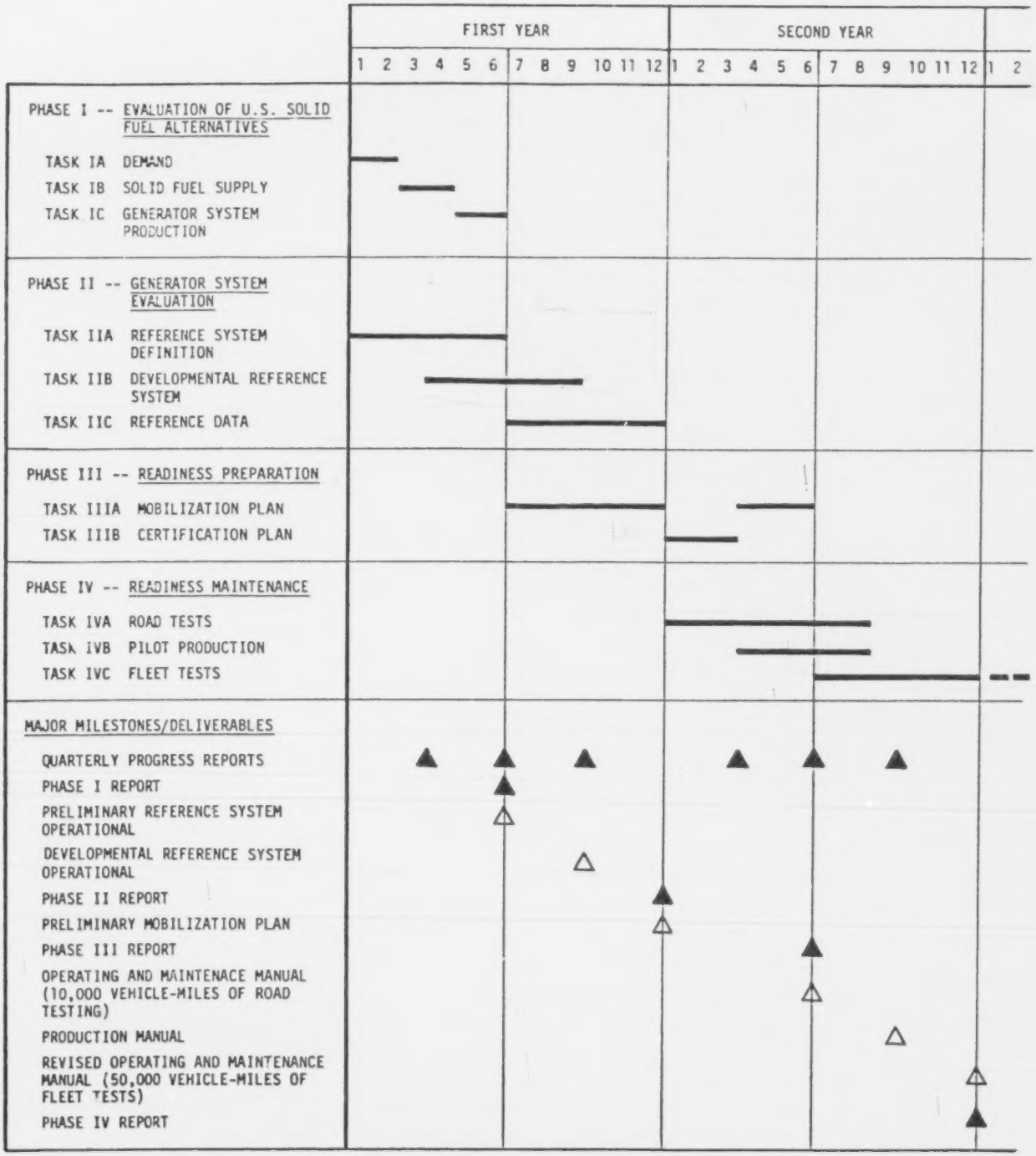

FIRST YEAR
SECOND YEAR
1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2
PHASE I -- EVALUATION OF U.S. SOLID FUEL ALTERNATIVES
TASK IA DEMAND
TASK IB SOLID FUEL SUPPLY
TASK IC GENERATOR SYSTEM PRODUCTION
PHASE II -- GENERATOR SYSTEM EVALUATION
TASK IIA REFERENCE SYSTEM DEFINITION
TASK IIB DEVELOPMENTAL REFERENCE SYSTEM
TASK IIC REFERENCE DATA
PHASE III -- READINESS PREPARATION
TASK IIIA MOBILIZATION PLAN
TASK IIIB CERTIFICATION PLAN
PHASE IV -- READINESS MAINTENANCE
TASK IVA ROAD TESTS
TASK IVB PILOT PRODUCTION
TASK IVC FLEET TESTS
MAJOR MILESTONES/DELIVERABLES
QUARTERLY PROGRESS REPORTS
PHASE I REPORT
PRELIMINARY REFERENCE SYSTEM OPERATIONAL
DEVELOPMENTAL REFERENCE SYSTEM OPERATIONAL
PHASE II REPORT
PRELIMINARY MOBILIZATION PLAN
PHASE III REPORT
OPERATING AND MAINTENACE MANUAL (10,000 VEHICLE-MILES OF ROAD TESTING)
PRODUCTION MANUAL
REVISED OPERATING AND MAINTENANCE MANUAL (50,000 VEHICLE-MILES OF FLEET TESTS)
PHASE IV REPORT

Fig. B-2 Program Task and Milestone Schedule

3.2 PHASE I -- EVALUATION OF THE U.S. SOLID FUEL ALTERNATIVE

The objective of this Phase is to obtain and organize the input information required to formulate a plan for the emergency utilization of the solid fuel alternative in the U.S. Existing literature and published statistics will be the primary source of data. Sufficient initial attention will be given to the foreign precident literature to define the key demand, supply and production factors. Direct correspondence or interviews with foreign and domestic agencies and companies will be employed when necessary to clarify key (current) issues not covered by the literature, and to determine the existence and status of similar planning in other countries or locally in the U.S. Emphasis will be on the gathering and organizing of information in this Phase rather than on seeking coherent interaction of the various aspects.

3.2.1 Task IA -- Demand

The requirements of potential U.S. users of solid fueled gas generators will be determined including type of application, power and type of engine served, and maximum tolerable costs. The number of generator systems needed will be estimated as a function of time, location and degree of petroleum shortfall.

3.2.2 Task IB -- Solid Fuel Supply

Using the required fuel properties consistent with Tasks IA and IIA, the location and production capacity of presently-available solid fuels in the various regions of the U.S. will be determined. Similarly, the multiple existing capabilities for packaging, distribution and marketing of solid fuels will be determined, including adaptation of the facilities presently used for other mass-retailed granulated solid products (e.g. salt, animal feeds, fertilizers, insulation, cement, etc.). Estimates will be made of the capacity for production, packaging, distribution and marketing as a function of time after the onset of a petroleum emergency shortfall.

3.2.3 Task IC -- Generator System Production

Based on the Reference System defined in Tasks IIA and IIB, the overall mass production requirements (man-hours, type of facilities, quantity of materials, etc.) will be defined for production of gas generator systems in the quantities estimated in Task IA. The location and capacity of the existing multiple capabilities for such production in the U.S., including estimates of small shops as well as large factories, also will be determined. Special attention will be given to the availability of labor and facilities which otherwise would be idled in an emergency shortfall (e.g. recreational vehicles, petroleum-consuming boats, automobile-related industries, etc.)

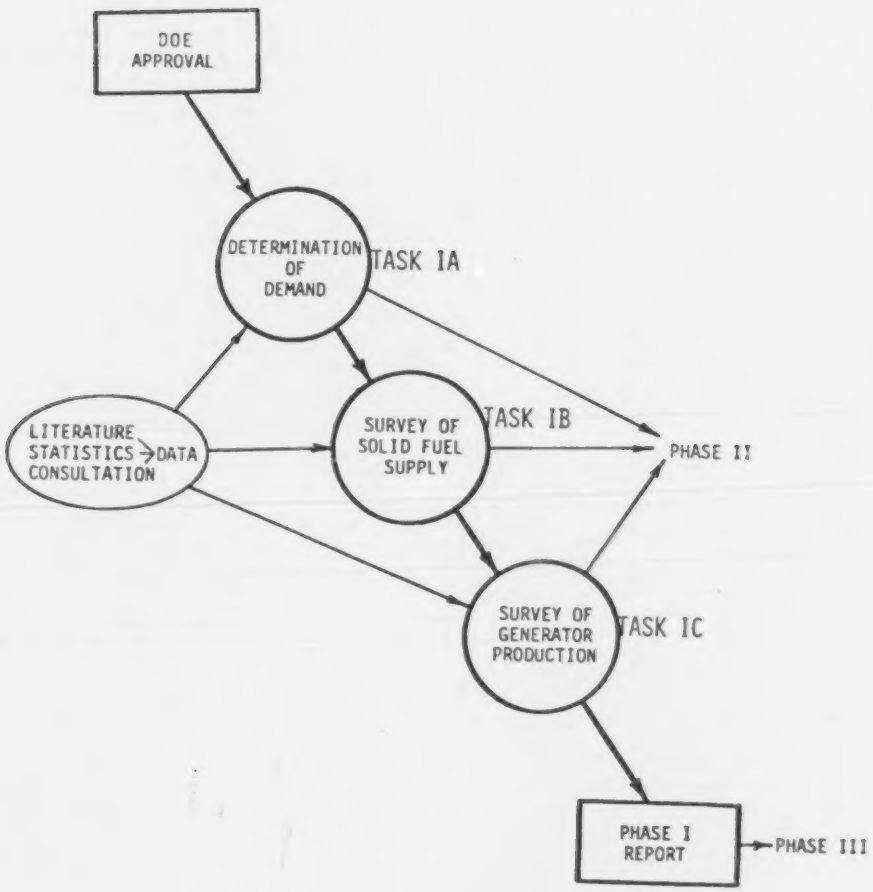


Fig. B-3 Phase I Strategy -- Evaluation of the U.S. Solid Fuel Alternative

3.3 PHASE II -- GENERATOR SYSTEM EVALUATION

The objective of this Phase is to select the best immediately-available solid fuel gas generator system for U.S. use in an emergency petroleum shortfall, and to experimentally test and establish its suitability for use with typical U.S. vehicles and fuels.

3.3.1 Task IIA -- Reference System Definition

Subtask IIA.1 -- Selection. All published types of formerly-produced gas generator systems will be surveyed and considered, and all such systems currently produced (domestic or foreign) will be sought and considered, to determine the best immediately-available system or systems for satisfying the U.S. requirements defined in Task IA.

Subtask IIA.2 -- Construction or Procurement. The selected system or systems will be constructed based on the best information available, or will be purchased if available commercially on a timely and cost-effective basis.

Subtask IIA.3 -- Acceptance Testing. The selected system (or systems) will be tested, including bench, dynamometer and road tests, to establish a fully-operational Preliminary Reference System, i.e. a system sufficiently well-defined for immediate mass-distribution of production drawings, bill of materials, and instructions for its construction, installation and use in the event of an emergency petroleum shortfall. The Preliminary Reference System is to be fully-operational within six months of initiation of the program.

3.3.2 Task IIB -- Developmental Reference System

Subtask IIB.1 -- Design Improvement Studies. As soon as construction or procurement is begun on the Preliminary Reference System, performance analysis and design studies are performed on the generator system selected to determine in what ways immediately-available modern technology can be employed to significantly upgrade its performance and utility. This will include but not be limited to incorporation of improved controls (e.g. use of existing electronic engine sensors and controls to optimize generator performance under variable demand), improved materials (e.g. high temperature hearth components and insulation), improved filter and ash disposal technology, improved pollution control, and configurational improvements which facilitate incorporation into a wide variety of modern vehicle and other applications.

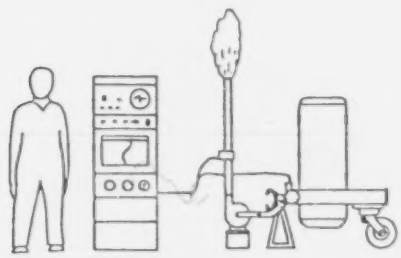
Subtask IIB.2 -- Construction or Procurement. An additional gas generator system, a Developmental Reference System which incorporates the design improvements found to be potentially significant in Subtask IIB.1, will be constructed or procured.

Subtask IIB.3 -- Improvement Evaluation Tests. The Developmental Reference System will be used to experimentally evaluate the efficacy of each of the design improvements, leading to a final design for the Reference System in the ninth month of the Program. Special attention will be given in this Subtask to determination of exhaust emissions during dynamometer tests, and to methods of suppressing pollutants. (Emissions are discussed on pages 7-2, 7-3, and 9-2 of Enclosure A).

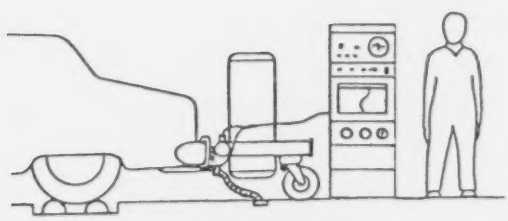
3.3.2 Task IIC -- Reference Data

Subtask IIC.1 -- Reference Generator Data. Parametric tests are performed first on the Preliminary Reference System and then on the final upgraded Reference System to establish the operating parameters associated with optimum performance using the Reference Fuels. These Reference Data will permit specification of initial generatory standards on which to base certification of future generator systems.

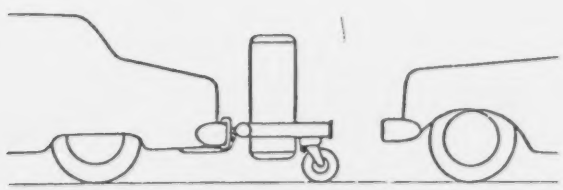
Subtask IIC.2 -- Reference Fuel Data. A group of typical fuels, defined by Task IB and IIIA as potentially most important for emergency use in the U.S., are characterized using their effects on the operating parameters of the Reference System. The acceptable limits for fuel properties (e.g. tar and ash content, reactivity, etc.) in each generic type of fuel (e.g. coal, coke, wood, characoal) are determined, and the best fuel within each type is selected to form a set of Reference Fuels for generator certification. The acceptable limits for fuel properties will permit specification of initial fuel standards on which to base certification of fuels.



BENCH TESTING



DYNAMOMETER TESTING



ROAD TESTING

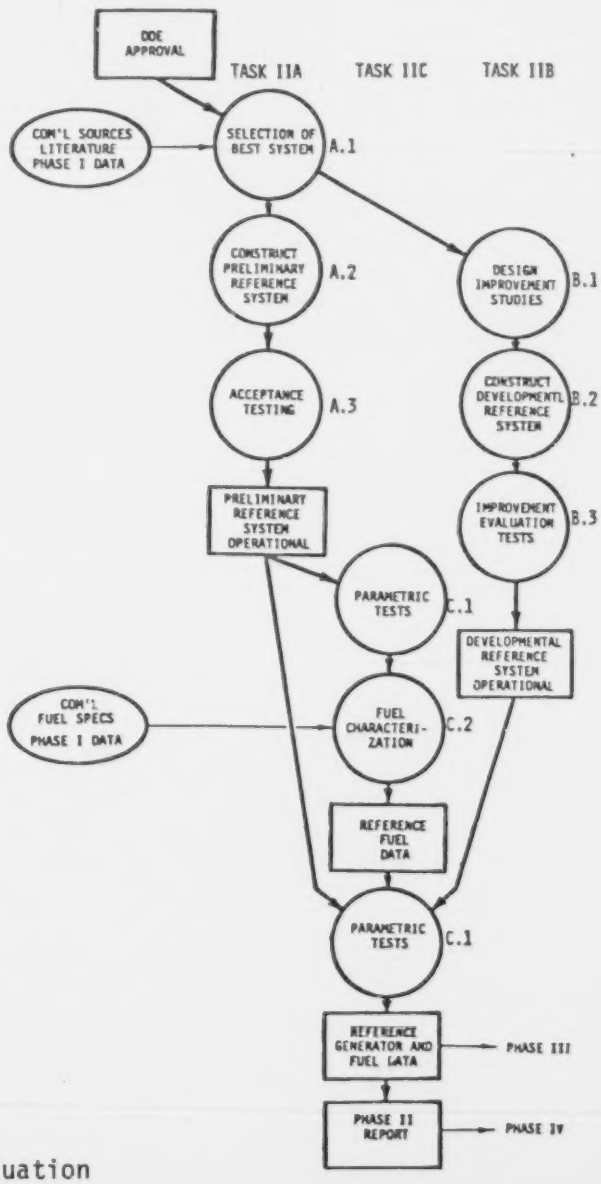


Fig. B-4 Phase II Strategy -- Generator System Evaluation

3.4 PHASE III -- READINESS PREPARATION

In this Phase the results of Phases I and II will be evolved into a coherent plan for effective initiation and efficient maintenance of the use of solid fueled gas generators in an emergency petroleum shortfall.

3.4.1 Task IIIA -- Mobilization Plan

A detailed staged plan will be prepared for emergency production and marketing of solid fuel gas generators and of the associated solid fuels. Supply and demand for generator systems and fuels will be compared and matched where possible for each logistically-characterizable region of the country. Representative potential suppliers will be contacted to estimate the probability, extent and rapidity of response by the private sector, with emphasis on determining the incentive thresholds required for adequate response, e.g. purely through profitability, or the additional need for government-provided incentives and assistance. Various scenarios will be considered to define the appropriate action that can be taken by federal, state and local governments in response to various degrees of shortfall and at each stage of development of emergencies of various types.

3.4.2 Task IIIB -- Certification Plan

Potential applicability in the United States of the highly successful gas generator certification used in Sweden during World War II will be evaluated. If judged to be sufficiently effective, provisions for establishment of certifying organizations will be incorporated into the Mobilization Plan. Certification test procedures, facilities and initial generator and fuel standards will be specified in conjunction with Task IIC.

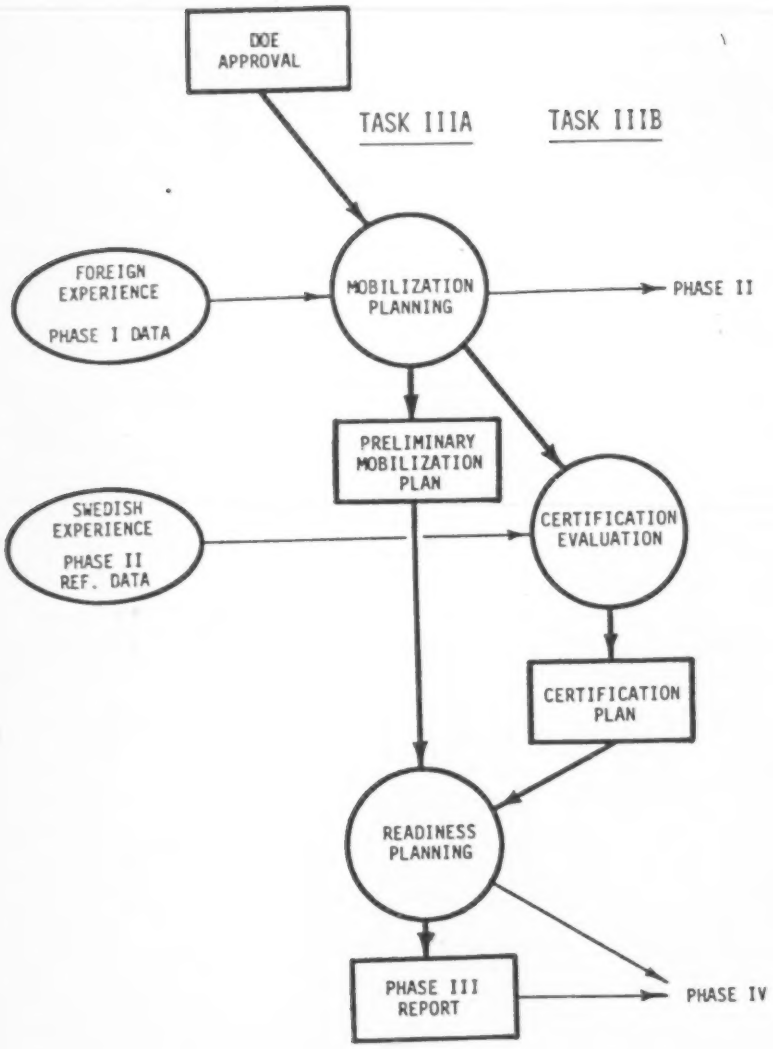


Fig. B-5 Phase III Strategy -- Readiness Preparation

3.5 PHASE IV -- READINESS MAINTENANCE

The purpose of this Phase is to rapidly gain practical experience in operation of the Reference System through its near-routine use in a variety of typical practical conditions, to accumulate many hours of use under these conditions to uncover failure modes, and to obtain sufficient public exposure and recognition prior to an emergency for rapid acceptance of the solid fuel alternative. In addition, pilot production in this Phase will provide prior experience on quantity production requirements. Continued use and production will progressively upgrade the technology base and maintain know-how as a nucleus for rapid large-scale emergency response.

3.5.1 Task IVA -- Engineering Road Tests

SubTask IVA.1 -- Construction or Procurement. Three Reference Systems will be constructed or procured and installed on at least three typical passenger cars of different sizes and ages.

Subtask IVA.2 -- Instrumented Tests. System performance on each car will be characterized initially in dynamometer tests using the reference fuels. The cars then will be driven on highways for extended periods with instrumentation and recorders to monitor their performance under practical conditions, and to uncover and diagnose potential or actual failure modes. Repeat dynamometer tests will be performed to detect and diagnose any long term performance degradation, and engines will be inspected for signs of abnormal wear or fouling.

Subtask IVA.3 -- Lay User Tests. After the instrumented tests are completed, the cars will be used by non-technical company employees for commuting and other "real world" conditions to evaluate the utility of the system for use by the general public. At least 10,000 total vehicle-miles of road testing will be accumulated in Task IVA within six months (i.e. by the end of the 18th program month).

Preparation of an Operating and Maintenance Manual for the Reference System is part of this Task.

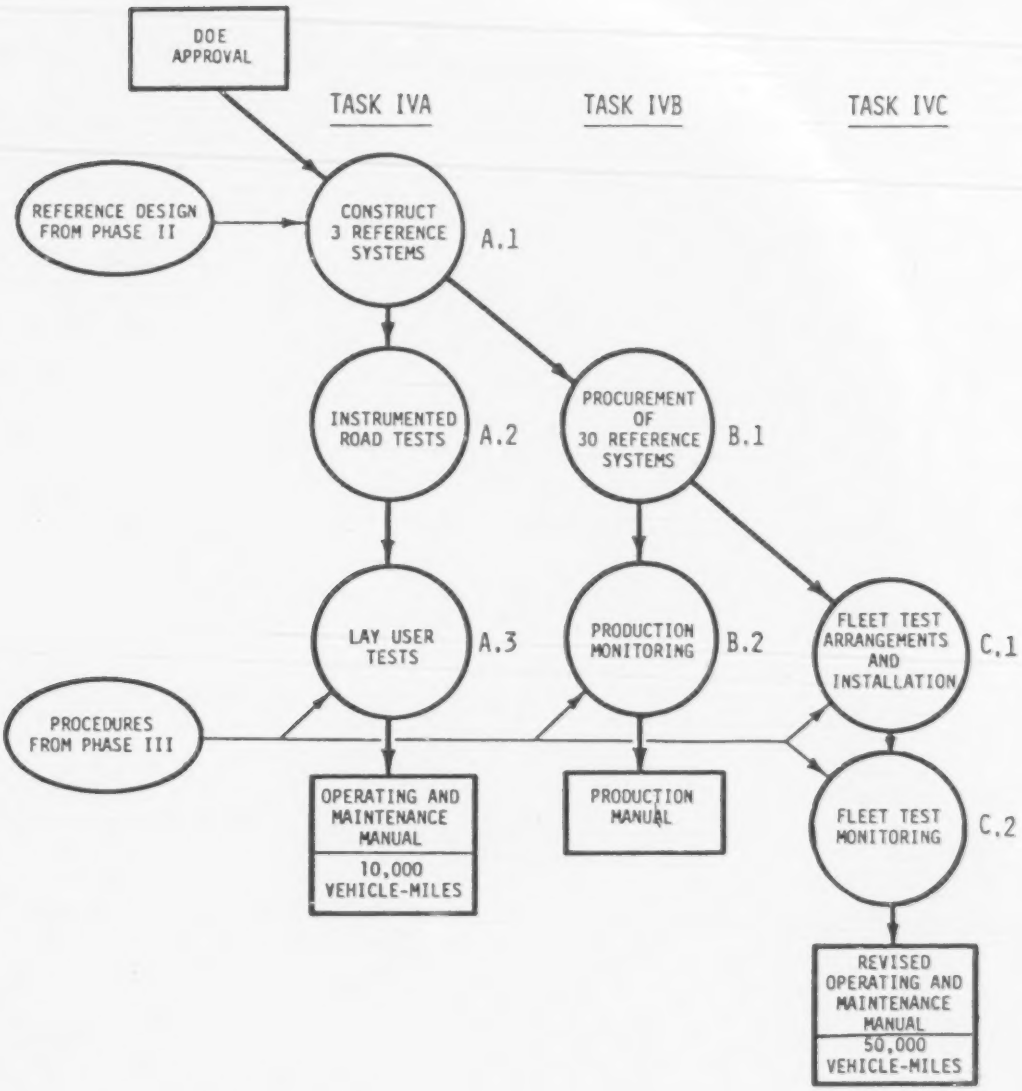


Fig. B-6 Phase IV Strategy -- Readiness Maintenance

3.5.2 Task IVB -- Pilot Production

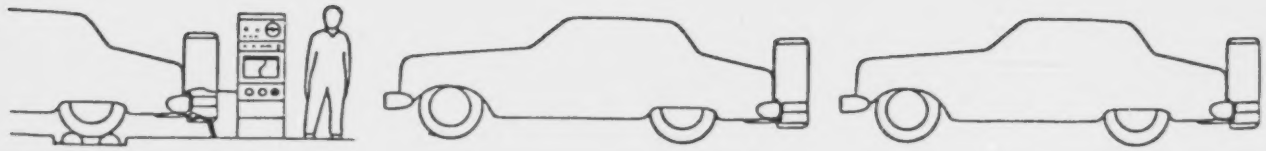
Subtask IVB.1 -- Procurement. At least 30 Reference Systems will be produced over a limited period by a competitively-selected subcontractor, with total price and prior relevant fabrication experience as determining factors in the competition.

Subtask IVB.2 -- Production. The production line will be observed during production, and detailed production records will be maintained. A Production Manual for the Reference System will be prepared.

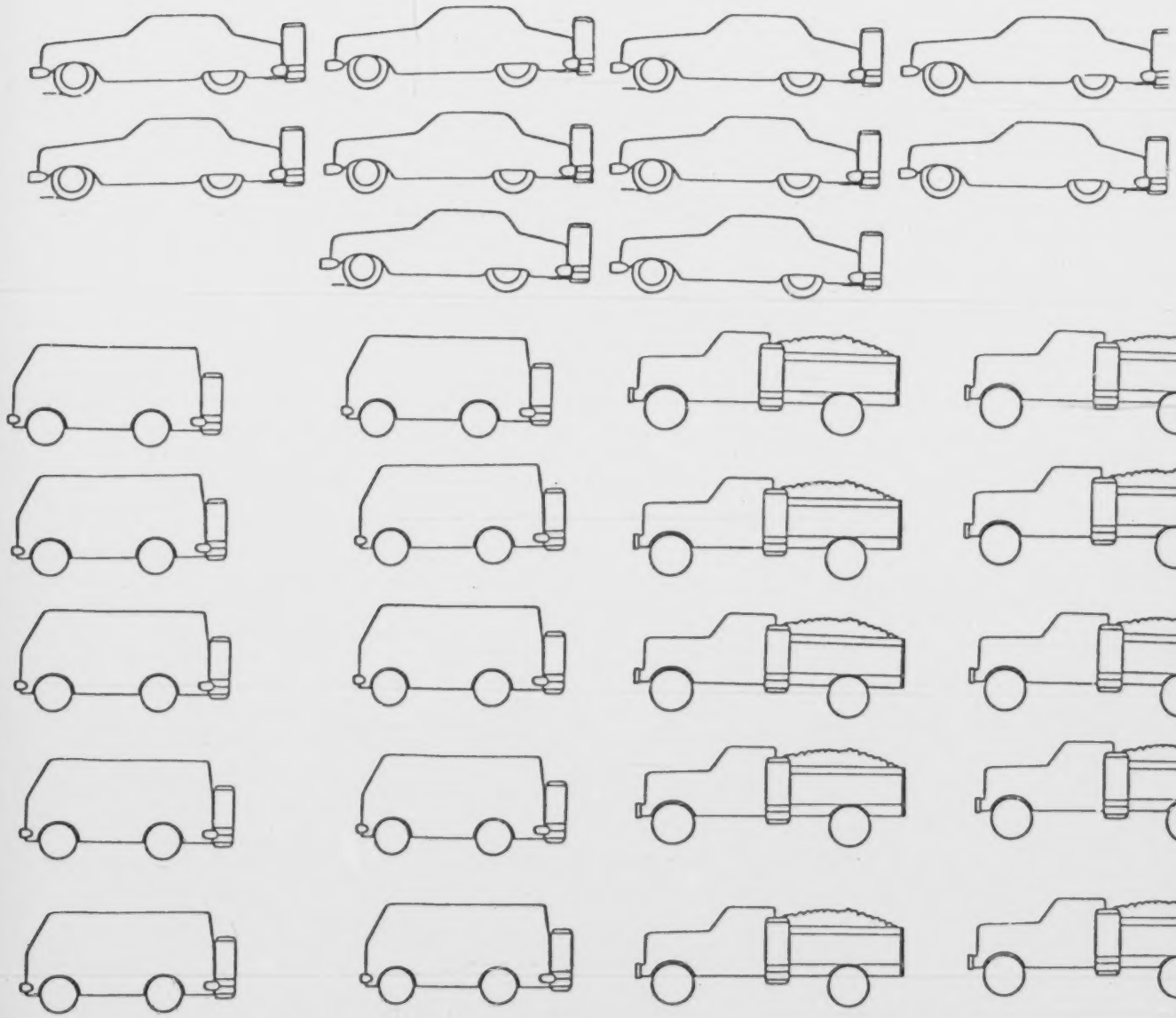
3.5.3 Task IVC -- Fleet Tests

Subtask IVC.1 -- Arrangements and Installation. The 30 Reference Systems produced in Task IVB will be installed on at least two vehicle fleets of at least ten vehicles each. These fleets will be trucks or cars owned and operated by organizations interested in promoting the use of solid fuels: e.g. coal or forest product companies, or state or local governments in coal or wood-producing regions. The fleets will be chosen to yield the greatest amount of generally-useful and typical operating experience. It is expected that the fleet owners will contribute to the funding of this Phase at least the amount of money which operation of the vehicle fleet otherwise would have cost them during the same period. Participation of state and local agencies will be sought.

Subtask IV.2 -- Coordination and Experience Logs. Fleet vehicle operating and maintenance personnel will be instructed on the use and maintenance of the Reference Systems, and they will maintain an Experience Log on each vehicle. These logs will be reviewed periodically and supplemented by personal interviews with those personnel. A total of at least 50,000 vehicle-miles of operating experience will be accumulated within six-months (i.e. by the end of the second program year). The Operating and Maintenance Manual will be revised to include this experience. Detailed operation of the fleet tests will draw heavily from the experience gained in similar fleet tests conducted for alcohol fuels by federal and state agencies.



ENGINEERING ROAD TESTS



FLEET TESTS

Fig. B-7 Readiness Maintenance

APPENDIX C

U.S. RESOURCES FOR EMERGENCY PRODUCTION OF MOBILE GASIFIERS

VALIDITY OF SWEDISH-U.S. MICROCOSM ANALOGY

It has not been possible yet to obtain the Swedish gross national product for circa 1940-1945. However, the per-capita GNP for Sweden and the U.S. are presently about the same, which implies a similar living standard and productivity for the two countries. It will be assumed that this similarity also existed in the 1940-1945 World War II era.

In the period September 1940 to March 1941, Sweden produced mobile gasifiers at the rate of about one per year for each 80 people in the total population. Productivity has increased at an average rate of about 4% per year for the 40 years since then in the U.S., such that this is now equivalent to a production rate of one per year for each 17 people. For the present U.S. population of about 230 million, this implies that production in the U.S. of about 14 million gasifiers per year would have about the same impact on the U.S. gross national product as the highest rate of production of gasifiers did in Sweden, assuming the same constraints on productivity in both countries during emergency conditions. The literature[1] indicates that the limiting factor was acceptance of gasifiers rather than production capability, however, so that this is the lower limit of potential gasifier production in the microcosm analogy.

SELECTIVE IMPACT ON U.S. INDUSTRY

Table C-1 is data, obtained from the most recent (1977) Census of Manufacturers conducted by the U.S. Department of Commerce, for the categories of manufacturers most likely to participate in the production of mobile gasifier systems (not including producers of raw material forms). It is estimated, based on Swedish statements[1] of gasifier prices and recent experience of Rasor Associates in producing a mobile gasifier, that 20-40 man-hours will be required to produce the complete system from the raw forms and widely-available standard components. The impact on the suppliers of these forms and components presumably will be about proportionately the same as on the listed organizations that are the normal users of their products. The breadth of this estimate results from the productivity difference between the assembly-line vs. one-at-a-time production characterization spanned by

TABLE C-1 1977 DATA FOR SELECTED U.S. MANUFACTURERS

	TYPE OF ORGANIZATION	NUMBER OF ORGANIZATIONS	PRODUCTION WORKERS (THOUSAND)	MAN-HOURS PER YEAR (MILLION)	PRODUCTION WAGES (MILLION)	VALUE ADDED (MILLION)	VALUE OF SHIPMENTS (MILLION)
	METAL BARRELS, DRUMS AND PAILS	180	10	20	130	390	940
	HEATING EQUIPMENT (NON-ELECTIVE)	701	19	36	190	740	1440
	FABRICATED PLATEWORK, BOILER SHOP	1860	88	172	1130	4080	7430
	SHEET METAL WORK	3430	57	110	640	2100	4860
	PREFABRICATED METAL BUILDINGS	466	16	32	170	690	1780
	MISC. FABRICATED METAL PRODUCTS	3243	54	105	550	1810	3430
	REFRIGERATION AND HEATING EQUIPMENT	860	104	205	1270	4470	9640
	INDUSTRIAL FURNACES AND OVENS	327	9	18	107	470	750
	HOUSEHOLD COOKING EQUIPMENT	96	19	37	197	784	1700
	HOUSEHOLD REFRIGERATORS, FREEZERS	42	30	57	360	1170	2580
	HOUSEHOLD LAUNDRY EQUIPMENT	31	16	29	200	840	1790
	FARM MACHINERY AND EQUIPMENT	2008	96	182	1310	4850	10280
	MOTOR VEHICLES AND CAR BODIES	322	290	620	5720	18720	76500
1	TRUCK AND BUS BODIES	820	27	54	308	950	2000
1	TRUCK TRAILERS	353	23	43	230	650	1910
	MOTOR HOMES	116	15	30	140	440	1560
2	BOAT BUILDING AND REPAIRING	2190	36	68	320	860	1820
2	TRAVEL TRAILERS AND CAMPERS	861	22	41	200	510	1580
	TOTALS	17,906	931	1,859	13,172	44,524	131,990

the organizations listed, although the relative complexity of the various possible gasifier system designs could further broaden this estimate. A nominal 30 man-hours will be selected as a mean requirement, which seems realistic in view of the fact that only about 80 man-hours are required by automotive production workers to produce a complete typical automobile.

It can be expected that many of the manufacturers listed may resist conversion of more than a nominal 10-20% of their productive capacity (i.e., their normal surplus capacity) to emergency production of gasifiers. It also can be expected, however, that others that are heavily impacted by the petroleum shortfall would convert most or all of their capacity to such production. In particular, the motor vehicle industry (category 1 in Table C-1) was heavily impacted during previous shortfalls, and the recreational vehicle industry (category 2) was brought to a virtual standstill. Together, these two categories represent almost half of the total number of production man-hours, and could be expected to have an abnormally high surplus capacity available during a petroleum shortfall. Accordingly, it is reasonable to expect that 20% of the 1860 million man-hours total in Fig. C-1 would be available for production of gasifiers at 30 man-hours per unit, resulting in production of 12 million gasifier systems per year by the industries listed.

In Sweden, as in many other countries where gasifiers were not centrally produced as part of an organized national war production, a significant fraction of the units (about 1/3 in Sweden[1]), were produced by garages, moonlighters, and others not ordinarily engaged in manufacturing. As an illustration of this productive potential in just one category, it can be noted that if 20% of the approximately 100,000 automobile repair and servicing garages in the U.S. were to produce one unit per day (six per week), this would result in production of about 6 million gasifiers per year.

It is reasonable to expect, therefore, that a surplus capacity able to produce 15-20 million gasifiers per year exists in the U.S. without having a major effect on the affected industries or an effect on the gross national product greater than that experienced by Sweden during conversion to gasifiers there. In fact, it is not unreasonable to expect that this number could be doubled (to a 40% utilization of the production base) under wartime

mobilization conditions. This capacity must be organized by a comprehensive pre-existing production and distribution plan if it is to be effective as early and as completely as in the Swedish experience, however.